Climate Policy and the Airline Industry: Emissions Trading and Renewable Jet Fuel

By

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Abstract

In this thesis, I assess the impact of the current EU Emissions Trading Scheme and a hypothetical renewable jet fuel mandate on US airlines. I find that both the EU Scheme up until 2020 and a renewable jet fuel mandate of 1bn gallons per year from 2018 to 2022 would have a small impact on US airlines and emissions, and operations would continue to grow by ~3% p.a.

I find that if carriers pass on all additional costs to consumers in the EU Scheme, including the opportunity costs associated with free allowances, windfall gains may be substantial at about \$2.6bn because under current allocation rules, airlines would only have to purchase about a third of the required allowances. However, an increase in the proportion of allowances auctioned would reduce windfall gains and profits for US airlines would decline. If airlines pass on only allowance expenses airlines do not receive windfall gains. Out-of-sector abatement is estimated at about a third of airline emissions for the North Atlantic routes, compared to the estimated 1.6% in-sector emissions reductions due largely to reductions in demand under the EU Scheme. Under proposed EU legislation, airlines can use renewable jet fuel instead of purchasing emissions allowances. I find that the current allowance price would make it cheaper for airlines to purchase renewable jet fuel only under conditions where the renewable fuel price premium is 10 cents per gallon or less.

I find that a renewable jet fuel mandate of 1bn gallons per year for US commercial aviation (about 4% of the total fuel use) with renewable jet fuel price premium of \$1.50 would increase airline fuel costs by ~2% and reduce greenhouse gas emissions by between 2% and 4%. Emissions would continue to grow and reach approximate 2018 levels by 2022.

I use the social cost of carbon, with a baseline value of \$100/tCO_2e, to calculate the societal cost-effective price premium of renewable jet. I find that fuels can have a price premium of between 40c and \$1.30 per gallon, depending on life cycle greenhouse gas reduction. Renewable jet fuels examined in this thesis, including the only commercially available fuel, currently have price premiums of more than \$2 per gallon and a calculated greenhouse gas abatement cost of more than \$250/tCO_2e.

This thesis shows that the emerging renewable jet fuel industry needs to reduce costs to achieve greenhouse gas abatement costs, and therefore societal benefits, comparable to the social cost of carbon or EU allowance costs. It also shows that for the fuels examined with currently estimated prices, the EU Scheme, and the now defunct Waxman-Markey Bill would be lower cost options of greenhouse gas abatement for airlines than a renewable fuel mandate, and in any case would not preclude the use of renewable fuels should they be produced with lower price premiums.

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Chapter 1

1 Introduction

1.1 Motivation

Air transport currently accounts for a small but increasing proportion of greenhouse gas emissions from human activity. In 2010 the air transport industry emitted 2% of global carbon dioxide emissions (IATA, 2011). Between 1971 and 2009, air transport's carbon dioxide emissions grew by 153% while global carbon dioxide emissions grew by 102% (IEA, 2010)[1]. The Intergovernmental Panel on Climate Change (IPCC) estimates that by 2050 air transport carbon dioxide emissions will account for 3% of carbon dioxide emissions from human activity (IPCC, 2007).

There is good evidence that carbon dioxide and other greenhouse gasses will change the earth's climate and pose risk to human and natural systems. The International Panel on Climate Change (IPCC) report in the *Climate Change 2007: Synthesis Report* that: "carbon dioxide is the most important anthropogenic greenhouse gas", and conclude that "there is very high confidence that the net effect of human activities since 1750 has been one of warming" (IPCC, 2007). In the United States, the National Academy of Sciences report that: "climate change is occurring, is very likely caused primarily by the emission of greenhouse gases from human activities, and poses significant risks for a range of human and natural systems" (NAS, 2011). Other scientific institutions agree. In October 2009 the American Association for the Advancement of Science (AAAS) and seventeen other groups, including the American Geophysical Union and the American Meteorological Society, wrote a letter to the United States Senate stating that: "observations throughout the world make it clear that climate change is occurring, and rigorous scientific research demonstrates that the greenhouse gases emitted by human activities are the primary driver" and that "the severity of climate change impacts is expected to increase substantially in the coming decades". (AAAS, 2006)

[1] In an analysis of 139 studies, Gillen et al. (2003) find that aviation has a median income elasticity demand of 1.39.

In the context of growing concern about climate change, there has been both national and international discussion about reducing aviation's carbon dioxide emissions. At the international level, the International Air Transportation Association (IATA) has implemented industry goals to cap aviation carbon dioxide emissions from 2020 (carbon-neutral growth), achieve an average improvement in fuel efficiency of 1.5% per year from 2009 to 2020 and reduce carbon dioxide emissions by 50% of 2005 levels by 2050 (IATA, 2009). In October 2010 the United Nation's International Civil Aviation Organization (ICAO) adopted resolution A37-19 (ICAO, 2010a) with similar aims to IATAs. In 2008, the European Commission adopted directive 2008/101/EC, to include aviation in the European Union (EU) Emissions Trading Scheme (ETS), effective January 1st 2012. Under the EU-ETS, all flights originating or departing from airports within the EU, irrespective of carrier nationality, have to acquire allowances to cover carbon dioxide emissions.

In the United States regulation pertaining to carbon dioxide emissions continues to be controversial. Although the United States ratified the 1997 Kyoto Protocol, no president has either signed, or rejected, the protocol. However, the United States has seen developments in terms of regulating greenhouse gas emissions. Since January 2011, The United States Environmental Protection Agency (EPA) has regulated greenhouse gas emissions from certain stationary and mobile sources under the Clean Air Act. Likewise, in June 2009 the House of Representatives approved The American Clean Energy and Security Act, also known as the Waxman-Markey Bill. The bill would have established a US emissions trading scheme. However, the bill did not pass a vote in the Senate (H.R.2454, 2009). In 2011 the United States Federal Aviation Administration announced Destination 2025 which includes the stated goal "...one billion gallons of renewable jet fuel is used by aviation by 2018". (FAA, 2011)

While these regulations and goals are likely to be of great importance in reducing aviation's carbon dioxide emissions, they may result in an effective increase in airline fuel cost, and resulting decrease in airline operations, as shown by Malina et al. (2012) and Winchester et al. (2011) for the EU-ETS and the Waxman-Markey Bill respectively. Air transportation is vital to the global economy and so the impacts of such policy should be carefully considered. In 2010 ICAO member airlines[2] carried 2.56 billion passengers and 48 million tonnes of freight using 24,684 aircraft (ICAO, 2010b) serving 3750 airports and resulting in 33 million people being employed by the airline industry and related tourism (ATAG, 2008). In 2007, the global air transport industry accounted for 7.5% of world GDP, or more than $3.5 trillion per year (ATAG, 2008). It is therefore important to adopt regulation that will both reduce greenhouse gas emissions, and have as little negative impact on air transport as possible. Given this background, in this thesis I set out to explore and compare the impact of select climate legislation on the United States aviation industry[3].

1.2 Research Approach

In this thesis I assess the impact of the European Union Emissions Trading Scheme (EU-ETS) on US aviation. I also investigate the impacts of a hypothetical renewable jet fuel mandate on US aviation as well as quantify the greenhouse gas abatement cost and abatement cost goals of select renewable jet fuel pathways.

These three research threads are intended to stand independently. However, there is much interaction and relevance between each section. The research is broken down into four research questions:

Research Question 1: What is the impact of the EU-ETS on US aviation?

Research Question 2: What are the GHG abatement costs of renewable jet fuels?

Research Question 3: What is the impact of a hypothetical renewable jet fuel mandate on US aviation?

Research Question 4: Is it currently cheaper for airlines to purchase renewable jet fuel or emissions allowances in an emissions trading scheme?

A brief overview of research methodology follows. Chapter 2 addresses research question 1. The chapter research methodology follows Winchester et al. (2011) and Jost (2011). An economy-wide computable general equilibrium (CGE) model is used in conjunction with an airline partial equilibrium model. The CGE model is used to determine the impact of the EU-ETS on fuel prices and Gross Domestic Product (GDP), and the partial

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[2] Comprising the vast majority of airline traffic with its 191 member countries.

[3] I select the US aviation industry because this research was partly funded by the US Federal Aviation Administration Office of Environment and Energy under FAA Award Number: 06-C-NE-MIT.

equilibrium model is further developed and used to assess the impact of the EU-ETS on US airlines. The chosen CGE model is the Emissions Prediction and Policy Analysis (EPPA) model. The EPPA model is a recursive dynamic model of the global economy that links GHG emissions to economic activity (Paltsev et al., 2005)[4]. I model the aviation industry using the Aviation Environmental Portfolio Management Tool for Economics (APMT-E). A Matlab and SQL script was written to connect EPPA and APMT-E. The APMT tool suite is designed to assess the effects of aviation on the environment, and APMT-E focuses on airline responses to policy changes. The model has been used in support of International Civil Aviation Organization/Group on International Aviation and Climate Change (2009) and International Civil Aviation Organization/Committee on Aviation Environmental Protection (2010) and is outlined by MVA Consultancy (2009). In the model, airlines can respond to carbon dioxide costs by raising prices (and flying less) and, when purchasing new aircraft, selecting more fuel efficient alternatives. The model is calibrated using 2006 data from the Bureau of Transport Statistics Form 41 PS2, ICAO and the Aviation Environmental Design Tool (AEDT) based on the System for Assessing Aviation's Global Emissions or SAGE.

To investigate research question 2, renewable jet fuel abatement costs, I apply an analytic relationships from the literature (CBO, 2010 and DEFRA, 2008), which I re-derive for my purpose. Research question 3, the impacts of a mandate, is investigated using a heuristic model and through a literature review and descriptive approach, and research question 4 is investigated by combining results from previous sections.

1.3 Thesis Contributions

This thesis adds to an extensive literature on the environmental impacts of aviation, for example Waitz et al. (2004) and IPCC (Penner et al., 1999). In terms of investigating the impact of climate policy on aviation, Winchester et al. (2011), investigate the impact of the Waxman-Markey Bill of US aviation. Although several authors have examined the impact of the EU-ETS on aviation e.g., Anger (2010), Wit et al. (2005), Mayor and Tol (2010), Vespermann and Wald (2010), Chapter 2 of this thesis adds to the literature by

[4] Note that the EPPA model was modified and run by Niven Winchester and Chris Gillespie from the Joint Program for the Science and Policy of Global Change at MIT.

providing a focused analysis on US aviation, as well as adding a welfare economic impact assessment. It also adds to the literature by quantifying when it is cost-effective for airlines to purchase renewable jet fuel as apposed to emissions allowances under recently proposed EU legislation.

Although the existing literature deals extensively with cost and environmental impacts of renewable jet fuels (Stratton et al. (2010), Hileman et al. (2009, 2010, 2011), Pearlson (2011), IATA (2010b)), chapter 3 adds to the literature in several ways. Section 3.2 relates renewable jet fuel greenhouse gas abatement cost to renewable jet fuel cost premium and life-cycle greenhouse gas (LC-GHG) emissions reduction. While other studies have looked into the greenhouse gas abatement cost of corn ethanol and biodiesel (DEFRA, 2008) and the greenhouse gas abatement cost to taxpayers of ethanol and biodiesel renewable fuel tax credits (CBO, 2010), this thesis relates greenhouse gas abatement cost of current renewable jet fuels. Further, this section adds to the literature by using the social cost of carbon to estimate goals for renewable jet fuel cost premium for different renewable fuel production pathways. This knowledge could be used by industry, airlines and policy makers to estimate fuel cost premium goals. Section 3.3 provides the first analysis of a hypothetical renewable jet fuel mandate.

1.4 Thesis Organization

The thesis is divided into five chapters. An overview of the remaining chapters follows.

Chapter 2 presents research background, approach, results and conclusions regarding the impact of the European Union Emissions Trading Scheme on US aviation (research question 1). This chapter is a slightly modified version of Malina et al. (2012), with an additional analysis of the opportunity for US renewable jet fuel production and consumption on the North Atlantic under the EU-ETS.

Chapter 3 addresses research questions 2, 3 and 4. Renewable jet fuel greenhouse gas abatement cost estimates are addressed and used in the section on assessing the impacts a hypothetical renewable jet fuel mandate.

Chapter 4 discusses and concludes the content of this thesis and provides recommendations for future research.

Chapter 2

2 The Impact of the European Union Emissions Trading Scheme on US aviation[5]

2.1 Introduction

In 2005, the European Union (EU) implemented an emissions trading scheme (ETS) for certain industries and installations to partially fulfill its obligations under the Kyoto framework to reduce greenhouse gas emissions (European Union, 2003). The EU-ETS is currently in its second phase (2008-2012) and a third phase will operate from 2013-2020. The EU will develop post-2020 climate policies according to future international policy developments and progress in the understanding of the science of global climate change (European Union, 2009a).

The EU-ETS sets progressively lower caps on annual greenhouse gas (GHG) emissions and caps 2020 emissions at 79% of 2005 emissions. The EU-ETS operates in all 27 EU member states plus Iceland, Liechtenstein and Norway. It covers carbon dioxide (CO_2) emissions and nitrous oxide emissions from installations in the energy sector such as power stations, combustion plants and oil refineries, and emissions from most other industrial installations (e.g., iron and steel works; and brick, cement, ceramics, lime, pulp, paper and board manufacturing).

In 2008, the European Commission adopted directive 2008/101/EC, which states that aviation will be included in the EU-ETS from the beginning of 2012 (European Union, 2009b). All flights to or from airports in the 30 ETS countries, irrespective of carrier nationality, will have to acquire allowances to cover CO_2 emissions. While the International Civil Aviation Organization (ICAO) and International Air Transport Association (IATA) generally support market-based policies to abate aviation emissions,

[5] Please note that this is a slightly modified version of the paper: "The Impact of the EU Emissions Trading Scheme on US Aviation", Robert Malina, Dominic McConnachie, Niven Winchester, Christoph Wollersheim, Sergey Paltsev and Ian A. Waitz, Journal of Air Transport Management, Volume 19, March 2012, Pages 36-41. http://dx.doi.org/10.1016/j.jairtraman.2011.12.004. My contribution to this paper included: APMT-Economics modeling, assisting with external data collection and analysis and assistance writing the journal article and editing.

the inclusion of aviation in the EU-ETS has been challenged outside the EU. Some foreign governments and airlines argue that EU-ETS in its current form is both unjustly harmful to airlines and contravenes international treaties, such as the Chicago Convention. In this connection, the US government has requested an exemption from the EU-ETS for US carriers. Additionally, some US airlines and their trade body, the Aviation Transport Association (ATA), have filed a case in the European Court of Justice. A court ruling is expected by early 2012 (Kanter, 2011, ATA, 2011)[6]. Other countries, such as China, are also calling for exemptions (Flottau et al., 2011). Under current EU legislation, an exemption may be granted for airlines from countries that implement measures "equivalent" to those in the EU to reduce GHG emissions (European Union, 2009b).

In extending the EU-ETS to aviation, the European Commission will allocate aviation allowances for 97% of average annual emissions from 2004-2006 in 2012, and 95% of the same historical average from 2013-2020. However, aviation emissions may exceed the quantity of aviation emissions allowances if aviation buys allowances from other sectors covered by the EU-ETS and/or purchases emissions credits from certain clean energy projects. Under current regulations, 85% of aviation emissions allowances will be granted for free (grandfathered) each year based on each carrier's market share in 2010, and 15% of allowances will be auctioned. However, EU legislation allows policy makers to revise the number of allowances grandfathered from 2015 onwards.

In our analysis, we assess the economic impact of including aviation in the EU-ETS on US airlines. Although several authors have examined the impact of the EU-ETS on aviation (e.g., Anger, 2010), to our knowledge, no study focuses on US aviation. We also add to the existing literature by assessing welfare changes in the aviation industry due to the EU-ETS.

This chapter has five further sections. Our modeling framework is detailed in Section 2.2. Section 2.3 presents and discusses our core results. We conduct a welfare analysis in Section 2.4, and a sensitivity analysis is implemented in Section 2.5. In

[6] In March 2012, Airlines for America (formerly Air Transport Association) formally ended this lawsuit against aviation's inclusion in the European Union's Emissions Trading Scheme (EU ETS) (ATW, 2012).

Section 2.6 we explore the opportunity for US airlines using renewable jet fuel under the EU-ETS. Section 2.7 concludes.

2.2 Modeling Framework

Following Winchester et al. (2011), we assess the impact of the EU-ETS on aviation by linking an economy-wide computable general equilibrium (CGE) model with a partial equilibrium model that focuses on the aviation industry. We use a CGE model to determine the impact of the EU-ETS on fuel prices and GDP, and simulate the impact of changes in these variables in a partial equilibrium model of the aviation industry.

Our chosen CGE model is the Emissions Prediction and Policy Analysis (EPPA) model. The EPPA model is a recursive dynamic model of the global economy that links GHG emissions to economic activity and has been widely used to evaluate climate policies (see, for example, Paltsev et al., 2007 and 2009). The model is described in detail by Paltsev et al. (2005).

We model the aviation industry using the Aviation Portfolio Management Tool for Economics (APMT-E). APMT-E is one of a series of models that is being developed by the FAA and the *Partnership* for Air Transportation Noise and Emissions Reduction Center of Excellence. The APMT tool suite is designed to assess the effects of aviation on the environment, and APMT-E focuses on airline responses to policy changes. The model has been used in support of US-ICAO/GIACC (2009) and ICAO/CAEP (2010) and is outlined by MVA Consultancy (2009). In APMT-E, airlines can respond to CO_2 costs by raising prices (and flying less) and, when purchasing new aircraft, selecting more fuel efficient alternatives. The model is calibrated using 2006 data.

APMT-E identifies 23 route groups (e.g., North Atlantic, Domestic US, North America-South America and Europe-Africa). As we wish to determine the impact of the policy on US airlines, our analysis focuses on the North Atlantic. Based on Kincaid and Tretheway (2007), in APMT-E, the price elasticity of demand on the North Atlantic for passenger travel is assumed to be -0.72 and -0.99 for freight.

Existing functionality in APMT-E does not allow us to consider at least two second-order effects of the EU-ETS on US airlines. First, we do not consider the impact of the policy on US carriers on routes outside the North Atlantic, such as decreased US domestic flights due to reduced connecting passengers from North Atlantic flights. Second, we do not consider asymmetric effects of the EU-ETS on competitiveness. For example, cost increases for US airlines transporting passengers to non-EU destinations via the EU relative to airlines that bypass the EU. This argument has been widely voiced by the EU aviation industry, but Albers et al. (2009) conclude that competitive distortions due to the EU-ETS will be small.

To evaluate the impact of the EU-ETS on US airlines, we need to identify impacts on the North Atlantic route by carrier nationality. APMT-E identifies airline nationality for passenger travel, but not for freight. We extend APMT-E using market share data from the International Air Transport Association (IATA, 2010) and the US Department of Transportation (US Department of Transportation, 2011a) to estimate freight transported by US carriers on the North Atlantic. We do not consider freight transported by passenger aircraft (belly freight).

Grandfathered permits will be allocated according to 2010 markets shares in total EU-ETS traffic, measured in revenue tonne kilometers (RTKs). In our APMT-E modeling exercises, augmented to identify freight by nationality, the 2010 market share of US carriers is 9%. We validate this figure using data from the Marketing Information Data Transfer (MIDT) database. The market share of US airlines in total European traffic using this database is 10.2%. However, our MIDT market share calculation is biased upwards, as we are only able to obtain cargo data for US operations on the Atlantic. Consequently, our calculations include US cargo to and from several non-European regions, including Africa, the Middle East and India. Additionally, the external calculations apply to traffic to, within and from all European countries, not just EU-ETS countries. For these reasons, and to be consistent with APMT-E baseline assumptions, our allocation of free allowances to US airlines is based on a 9% market share. We consider a US market of 11% in a sensitivity analysis.

Our analysis focuses on the period 2012-2020. We limit our analysis to this time frame as the third phase of the EU-ETS will end in 2020 and information on future provisions is not currently available. We do not consider climate policies in regions other than the EU, so we do not model potential interdependencies between policies imposed by different regions. APMT-E does not identify individual carriers, so our results represent average industry impacts.

To investigate the impact of the EU-ETS on US aviation, we compare three scenarios with a reference case ("business as usual", BaU). Our reference scenario is based on US-ICAO/GIACC (2009). As we aim to examine the incremental impact of including aviation in the EU-ETS, we modify US-ICAO/GIACC forecasts to account for the impact of the EU-ETS on other sectors. Specifically, using predictions from an EPPA simulation of the EU-ETS that excludes aviation, we update US-ICAO/GIACC fuel prices and demand forecasts. Also, guided by Lee et al., (2001), we assume an annual increase in the fuel efficiency for new aircraft of 1.4%, rather than 1% in the US-ICAO/GIACC forecast. We consider a case with a 1% annual increase in fuel efficiency as a sensitivity study.

In our scenarios, we calculate an effective fuel price, which is equal to the BaU fuel price plus the cost of CO_2 emissions from fuel combustion. The price of CO_2 emissions allowances hovered around €15 per tonne of CO_2 (tCO_2) for most of 2010 (European Energy Exchange, 2011). There is also evidence that firms are banking allowances for use in later years (Grubb et al., 2009). Consequently, we assume a carbon price of €15/tCO_2 in 2010 and increase the price by 4% each year. Our 4% annual increase is approximately equal to the current yield on 10-year German bonds, a low-risk investment, plus a 1% risk premium. EU legislation prevents airlines from selling allowances to other sectors, but there are no restrictions on airlines purchasing allowances from other sectors. Under these regulations, the price of aviation allowances could differ from that for other sectors. However, empirical evidence (e.g., Winchester et al., 2011) and our simulations indicate that CO_2 abatement costs are higher for aviation than other sectors, so it is likely that aviation will purchase allowances from elsewhere. Therefore, we assume that there is a single price of CO_2 allowances for all EU-ETS covered sectors. Values in APMT-E are expressed in US dollars. We convert euro values to dollar values using a purchasing power parity (PPP) exchange rate of 1.24 dollars per euro (OECD, 2011).

Airlines' cost pass-through behavior is an important determinant of the impact of the EU-ETS on aviation. Consistent with profit maximizing behavior in competitive markets, most studies assume that airlines will pass on the full cost of CO_2 allowances, including opportunity costs associated with 'free' allowances. However, airfares may rise by less than the cost of CO_2 allowances for at least two reasons. First, there may be opportunity benefits from using free allowances. Opportunity benefits arise when current traffic is used to determine future allowance allocations. The presence of opportunity benefits creates an incentive for airlines to reduce fares (and expand demand) relative to a case without opportunity benefits. If there are opportunity benefits, airfares will increase by less than the cost of allowances or may decrease.

The allocation of free allowances for aviation in the EU-ETS is currently based on a one-off benchmark using market share data for 2010, measured in RTKs. This benchmark will likely be used until 2020. If the EU follows current regulation, future allocations will be based on market shares in the year ending 24 months before the start of the next trading period (2020). As operations from 2012-2017 and from 2019-2020 would not influence the share of free allowances allocated post 2020, opportunity benefits are unlikely to be present in these years. Opportunity benefits may exist in non-benchmark years, if current market shares depend on past operations, but incentives to inflate market shares in non-benchmark years are likely to be second order. Overall, we expect opportunity costs to be passed on to consumers during all years except 2018.

In 2018, opportunity benefits may exist, but would depend on the proportion of allowances grandfathered for future years. Although there are no historical observations for aviation, the European Commission has decreased the share of allowances grandfathered to other sectors over time. For example, nearly all allowances were grandfathered in the first trading period (2005-2007) and in the third trading period (2013-2020) around 50% of allowances will be grandfathered (European Commission, 2009b). This indicates that the number of allowances which are granted for free to airlines may be reduced, once the introductory trading period for aviation ends in 2020. It therefore appears that opportunity benefits in 2018 will be small.

Market distortions due to imperfect competition are a second reason why airlines might not fully pass on additional costs. Economic theory suggests that full cost pass-through will occur in competitive markets, in which prices reflect marginal production costs and no abnormal profit margins are present. That is, the absence of significant profits leaves no room for firms to absorb costs without going bankrupt. If a firm has market power, however, it can charge a price that exceeds marginal production costs and earn higher profits than in a competitive market. The existence of profits leaves room for firms to raise prices by less than the increase in costs without going bankrupt. Under most theories of imperfect competition, an airline will absorb a proportion of costs increases, so fares will increase by less than the cost of CO_2 allowances.

While several empirical studies investigate market structure and cost pass-through for other industries (e.g., Sijm et al., 2006, Ellerman and Joskow, 2008; and Butraw and Palmer, 2008), few studies focus on the airline industry. One exception is Forsyth (2008), which concludes that full cost pass-through is a likely outcome, if airlines do not have substantial market power.

The number of suppliers is sometimes used to infer market power. Airline schedule data for June 2011 shows that 91% of all routes (defined as airport pairs) on the North Atlantic are served by one or two carriers. At face value, this suggests that airlines have market power on most North Atlantic routes. However, a small number of carriers on a particular route may not be a good indicator of market power as (a) some airport-pairs serve overlapping catchment areas (e.g., EWR-LHR and JFK-LHR), (b) direct routes may compete with routes involving a connecting flight (e.g., FRA-SFO and FRA-BOS-SFO), (c) connecting passengers for whom the non-stop flight is only part of their journey might select other itineraries (e.g., SFO-AMS-BUD instead of SFO-FRA-BUD) and (d) the threat of entrants (except in congested airports such as FRA, JFK, LHR and ORD) may prevent airlines from offering fares significantly greater than costs.

To assess actual market power on the North Atlantic, it is informative to examine profit margins. According to data from the Bureau of Transportation Statistics (US Department of Transportation, 2011b), the annual average profit margin for Atlantic divisions of US airlines was 3.4% of operating revenue between 2000 and 2010, and 3.8% between 2006 and 2010. These profit margins are lower than the average profit margin for publicly listed US companies, which was 5.3% between 2000 and 2010 and 4.8% between 2006 and 2010 (Damadoran, 2011). Therefore, we conclude that the North Atlantic market for air services is, on average, competitive. This conclusion is consistent with the antitrust immunity analyses conducted by the US Department of Transportation.

In its tentative decision to grant antitrust immunity for a joint venture between oneworld airlines on some North Atlantic operations, the US Department of Transportation stated that, "no single airline [on the North Atlantic] has a dominant share of nonstop passengers, indicating a general competitive market" (US Department of Transportation, 2010).

Overall, because we conclude that opportunity benefits are likely to be small and that the North Atlantic route is competitive, we believe airlines are likely to pass on all costs associated with CO_2 allowances. When firms pass on all costs (including opportunity costs) and allowances are grandfathered, firms receive windfall gains (William-Derry and de Place, 2008). Nevertheless, we acknowledge that imperfect competition among airlines and the presence of opportunity benefits may result in airfares rising by less than the cost of CO_2 allowances. To account for uncertainty about airline behavior and opportunity benefits, we consider three scenarios.

In our first scenario, FULL, we assume that airlines pass on all costs associated with CO_2 allowances, including opportunity costs for free allowances. Airlines pass on expenses from purchasing allowances but not opportunity costs for free allowances in our second scenario, which we label EXPENSE. In our third scenario, ABSORB, airlines do not pass on any costs associated with CO_2 allowances. The three scenarios cover a broad spectrum of airline responses to the EU-ETS. As noted above, we believe the FULL scenario is the most accurate representation of future airline behavior.

To foreshadow our results, the largest rise in airfares and decreases in traffic and CO_2 emissions will occur in the FULL scenario. We also expect profits to increase in the full scenario, as airlines receive a large proportion of allowances for free and pass on opportunity costs of these allowances to consumers. Airfares will increase and traffic and CO_2 emissions will decrease in the EXPENSE scenario, but by smaller amounts than in the FULL scenario. In the ABSORB scenario, there will be no change in airfares, traffic, or CO_2 emissions, and profits will decrease.

2.3 Results

As noted in Section 2, we start from an emissions price of €15/tCO2 in 2010 and increase the price by 4% each year. Using a PPP exchange rate, the CO_2 price, in 2010 dollars, is

\$20/tCO_2 in 2012 and rises to \$27.45/tCO_2 by 2020. The price of a gallon of jet fuel in BaU is \$2.29 in 2012 and \$2.77 in 2020. Our BaU fuel prices are an extrapolation of 2006 (the base year for APMT-E) fuel prices based on long-run forecasts and accounting for the impact of the EU-ETS applied to other sectors. As such, our BaU prices do not necessarily reflect current fuel prices, which can be influenced by business cycles and speculation. When aviation is included in the EU-ETS, the effective price of jet fuel (including CO_2 allowance costs) when flying to or from the EU in 2020 is \$2.82 per gallon, 10% higher than in BaU.

Table 1 presents cumulative modeling results for US carriers on the North Atlantic for the period 2012-2020. We evaluate cumulative traffic changes by calculating the compound annual growth rate (CAGR) for RTKs. In the FULL scenario, demand decreases relative to BaU but RTKs continue to grow. Between 2011 and 2020, RTKs increase by 31.8% in the FULL scenario, compared to 34.5% in BaU. Airfare increases are smaller when airlines only pass on the costs of purchased allowances rather than all costs, so the annual growth rate for RTKs in the EXPENSE scenario exceeds that in the FULL scenario. There are no changes in RTKs in the ABSORB scenario relative to BaU, as airfares are the same in the two scenarios.

Table 1. Cumulative US carrier outcomes on the North Atlantic, 2012-2020.

	BaU	FULL	EXPENSE	ABSORB
RTKs (CAGR, %)	3.35	3.11	3.25	3.35
CO_2 emissions (CAGR, %)	1.72	1.49	1.63	1.72
CO_2 Emissions (tonnes, million)	210.10	206.74	208.93	210.10
Allowances purchased (million)	-	71.13	73.31	74.48
Out-of-Sector CO_2 Reductions (million)	-	71.13	73.31	74.48
Share of allowances purchased (%)	-	34.40	35.09	35.45
NPV of purchased allowances (\$, billion)	-	1.37	1.41	1.43
Operating costs, NPV (\$, billion)	143.02	141.76	143.50	144.45
Operating revenue, NPV (\$, billion)	147.37	148.62	147.81	147.37
Operating revenue per RTK, NPV (\$/RTK)	0.87	0.89	0.88	0.87
Profit margin (%)	2.95	4.62	2.92	1.98
Net US to EU transfer, NPV (\$, billion)	-	-1.24	1.41	1.43

Increases in traffic drive increases in CO_2 emissions, but emissions increases are smaller than traffic increases as the fleet becomes more efficient over time. The lowest annual growth in emissions occurs when airlines pass on all costs associated with CO_2 allowances. Table 1 also reports cumulative CO_2 emissions between 2012 and 2020. Comparing emissions for or policy scenarios to the BaU indicates that 3.35 million tonnes of CO_2 are abated in the FULL scenario and 1.17 million tonnes in the EXPENSE scenario. These numbers represent small proportional decreases in emissions relative to BaU – 1.6% in the FULL scenario and 0.6% in the EXPENSE scenario. Annual CO_2 emissions from US airlines on the North Atlantic increase from 21.9 million tonnes in 2011 to 25.2 million tonnes in 2020 in the BaU, and to 24.7 million tonnes in the FULL scenario. In the FULL scenario, US airlines purchase approximately 71.13 million emissions allowances. This is estimated to lead to out of sector abatement of 71.13 million tonnes CO_2 in the EU between 2012 and 2020, or about one third of total US airline emissions for the North Atlantic routes. All airlines purchase about 840 million emissions allowances which leads to the abatement of about 840 million tonnes CO_2 between 2012 and 2020, or approximately 2% of all EU emissions (UNFCC, 2008).

Although emissions abated by aviation differ across scenarios, abatement aggregated across all sectors is constant due to the economy-wide emissions cap. That is, the increase in aviation emissions is facilitated by purchasing allowances from sectors with lower abatement costs. In this connection, our EPPA simulations indicate that EU electricity emissions will be 57% below 2012 emissions in 2020. Between 2012 and 2020, in the FULL scenario, US airlines purchase allowances for about one-third of total allowances required by US airlines. Allowance purchases are largest in the ABSORB scenario, as traffic is largest in this scenario.

Net present values (NPVs) for financial indicators for US operations on the North Atlantic during the period 2012-2020 are presented in the second half of Table 1. Our NPV calculations use a discount rate of 4%, which is similar to the discount rate recommended by the US Office of Management and Budget (2003). As airfares in the ABSORB scenario equal BAU airfares, total operating costs rise by the cost of allowances in this scenario. In the EXPENSE scenario, the increase in airfares reduces traffic and operating costs net of CO_2 costs. However, the cost of purchasing CO_2

allowances results in a rise in total costs relative to BaU. Total costs decrease in the FULL scenario, as decreases in cost due to reduced traffic exceed the cost of purchasing allowances.

Operating revenues are a function of traffic and air fares. As demand is inelastic, the revenue impact of reduced RTKs is more than offset by an increase in airfares in the FULL scenario, so operating revenues increase. Operating revenue also increases in the EXPENSE scenario. Airfares and traffic in the ABSORB scenario are unchanged relative to BaU, so there is no change in operating revenues. Decreased RTKs and increased revenue result in revenue per RTK increasing in both the FULL and EXPENSE scenarios.

The impact of the policy on profit margins is of key interest to airlines. We calculate average profit margins for the period 2012-2020 by dividing the NPV of operating revenues by the NPV of operating costs. Airlines pass on the cost of purchasing allowances in the EXPENSE scenario, so the profit margin in this scenario is very similar to the profit margin in BaU. However, total profits decrease relative to BaU because the profit margin is earned on a lower volume. In the ABSORB scenario, as airlines incur additional costs that are not passed on, the average profit margin decreases. In the FULL scenario, there is a large increase in the profit margin because, in addition to the cost of purchasing allowances, airlines pass on opportunity costs associated with grandfathered allowances. Windfall gains from grandfathering are worth $2.6 billion in the FULL scenario.

Windfall gains from free allowances represent a transfer from the EU to the US. However, allowances purchased by US airlines from the European Commission and from EU firms represent a transfer from the US to the EU. In the FULL scenario, the NPV of free allowances exceeds the value of purchases resulting in a net transfer from the EU to the US. In the EXPENSE and ABSORB scenarios, there are no windfall gains, which result in net transfers from the US to the EU. Consistent with the scope of our economic analysis we do not address the distribution of environmental damages associated with the US aviation operations on the North Atlantic, although we anticipate impacts in both the EU and US (in addition to other impacts globally).

To summarize our analysis so far, for all cost pass-through assumptions, traffic and CO_2 emissions continue to increase over time when aviation is included in the EU-ETS. When some CO_2 costs are passed on to consumers, there are small decreases in emissions relative to BaU. Unlike CO_2 emissions, the impact of the EU-ETS on airline profitability varies widely for alternative cost pass-through assumptions. If there is full cost pass-through, which we believe is the most likely case, US airlines will experience a windfall gain of $2.6 billion over the period 2012-2020 from the granting of free allowances. On the other hand, if airlines are only able to pass on the costs of allowances purchased or are unable to pass on any costs, US airline profits will decrease.

Our analysis has focused on the operations of US airlines on the North Atlantic, which accounts for about 12% of total operations for US airlines measured in RTKs. To gauge the overall impact of the EU-ETS on US aviation, we report selected metrics for total US operations in Table 2. The results indicate that the EU-ETS will have a very small impact on aggregate RTKs and CO_2 emissions. In the FULL scenario, which generates the largest decrease in emissions, total US airline CO_2 emissions fall by only 0.19% relative to BaU. Similarly, for all scenarios, there are small changes in operating revenues, operating costs and profit margins relative to BaU. These results indicate that the EU-ETS will have a relatively small impact on the overall operations of US airlines.

Table 2. Cumulative US carrier outcomes on all routes, 2012-2020.

	BaU	FULL	EXPENSE	ABSORB
RTKs CAGR (%)	3.65	3.62	3.63	3.65
CO_2 Emissions (tonne, million)	2,139	2,136	2,138	2,139
Operating costs, NPV ($, billion)	1,589	1,588	1,590	1,591
Operating revenue, NPV ($, billion)	1,637	1,639	1,638	1,637
Profit margin (%)	2.92	3.07	2.92	2.83

2.4 Welfare Analysis

Policies such as the EU-ETS aim to reduce future damages from global warming. Benefits from avoided climate damages will not be limited to aviation, but will occur across the global economy. Additionally, the impact of the EU-ETS will depend on policies in other nations. Ellerman and Buchner (2007 and 2008) discuss the effectiveness of the EU-ETS in mitigating climate change, but a similar analysis is beyond the scope of our study. Instead, we evaluate the cost of including aviation in the EU-ETS within the aviation sector and investigate the distribution of costs across airlines and consumers. Our welfare calculations only concern aviation operations on the North Atlantic.

We use producer surplus, measured by operating profits, to calculate costs to airlines and consumer surplus to evaluate costs to consumers. Aviation consumers include travelers, consignors and freight recipients. We assume a linear demand curve to calculate changes in consumer surplus. For each year and scenario, the change in consumer surplus, ΔCS, is given by:

$$\Delta CS = \frac{1}{2}(q_0 + q_1)\times(p_0 - p_1) \qquad 2.1$$

where q_0 and q_1 are North Atlantic air traffic (measured in RTKs) in, respectively, BaU and the policy scenario; and p_0 and p_1 are airfares in BaU and the policy scenario respectively.

We summarize annual changes in producer surplus and consumer surplus by calculating NPVs for each measure aggregated over the period 2012-2020, again using a discount rate of 4%. Although it would be informative to calculate welfare changes specifically for US producers and consumers, our modeling framework does do not track consumers by country of origin. Additionally, although there are estimates of future US passengers on the North Atlantic, there is little guidance on how to measure consumer benefits from freight. Instead, we calculate consumer surplus changes for all consumers on the North Atlantic. To facilitate comparison of producer surplus changes with consumer surplus changes, we also calculate producer surplus for all North Atlantic carriers.

Table 3. Cumulative consumer and producer surplus changes relative to BaU ($, billion), 2012-2020.

	FULL	EXPENSE	ABSORB
Consumer surplus, all consumers, NPV	-11.39	-4.04	0.00
Producer surplus, all airlines, NPV	6.39	-0.08	-4.89
Producer and consumer surplus, NPV	-5.00	-4.12	-4.89

Table 3 presents NPV consumer and producer surplus changes relative to BaU for the 2012-2020 period. In the FULL scenario, consumer surplus decreases, due to higher fares and less traffic. Producer surplus increases in this scenario, as windfall gains more than offset the impact of reduced traffic. There is a smaller decrease in consumer surplus in the EXPENSE scenario, as airfare increases are smaller in this scenario than in the FULL scenario. There is little change in Producer Surplus in the EXPENSE scenario, as airlines pass on the costs of purchasing permits and there are no windfall gains. In the ABSORB scenario, there is no change in consumer outcomes and producer surplus decreases.

The sum of changes in consumer and producer surplus is negative in all scenarios. This result is not surprising, as the EU-ETS imposes additional costs on airlines and we do not consider benefits from emissions abatement or revenue from purchased allowances. However, as noted above, the inclusion of aviation in the EU-ETS is expected to reduce EU emissions by about 840 million tonnes CO_2. The change in social surplus differs across scenarios, but the numbers do not indicate that a particular cost pass-through behavior is preferable, as we do not consider interactions with other sectors. For example, greater demand for allowances in the ABSORB scenario relative to other scenarios, will increase the price of allowances and decrease consumer surplus in other sectors.

2.5 Sensitivity analysis

A key finding in our analysis is that the EU-ETS will have a relatively small impact on aviation emissions. This result is driven by high marginal abatement costs in aviation relative to other sectors and is consistent with findings from other studies (e.g., Winchester et al., 2011). Consequently, we do not investigate the sensitivity of this result to our modeling assumptions. Our finding that the EU-ETS may increase profits for US airlines is potentially more controversial. Influential drivers of this result, which we consider in sensitivity analyses, include future demand for air services on the North Atlantic, and the number of allowances grandfathered. We also examine the sensitivity of our results to the annual increase in the fuel efficiency of new aircraft, and the market share of US airlines in total European operations. The EU-ETS has little impact on profits in the EXPENSE scenario, so our analysis focuses on the FULL and ABSORB scenarios.

Our BaU demand forecasts are derived from US-ICAO/GIACC estimates. Faster or slower underlying demand growth will influence the quantity of allowances required by aviation and ultimately airline profitability. Demand for air services on the North Atlantic grew by 3.4% per year in the core scenarios. In separate sensitivity analyses, we consider demand growth rates of 2.4% and 5.5% in both BaU and our policy scenarios.

Figure 1 displays proportional changes in average 2012-2020 profit margins relative to BaU for the core demand growth scenario and for low and high demand growth alternatives. In high-growth scenarios, airlines need to purchase more allowances than in our base case and fewer in low-growth scenarios. In the FULL scenario with high growth, the relative contribution of (fixed) windfall gains decreases, so the increase in profit margin is lower than in the core FULL scenario. The opposite is true in the FULL scenario with low growth. In the ABSORB scenario, airlines also have to purchase more allowances if there is higher demand growth. Consequently, the average profit margin in the high growth scenario decreases by a larger amount than in the corresponding core scenario.

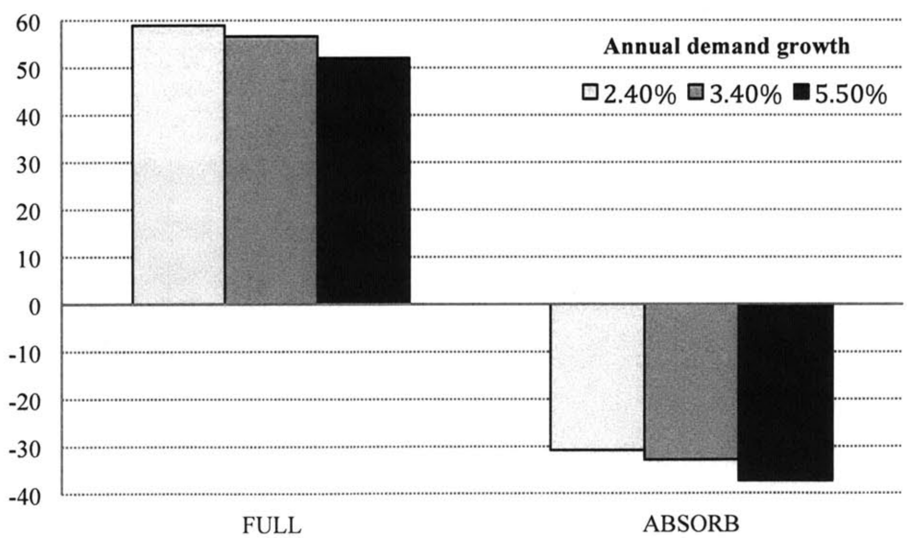

Figure 1. Changes in 2012-2020 average profit margins relative to BaU for alternative demand forecasts, %.

Regarding allowance allocations, we followed current legislation in our core scenarios and assumed that allowances for 85% of 2010 emissions will be grandfathered each year from 2012 to 2020. However, EU regulations provide scope for changes to allocation rules from 2015 onwards and the European Commission has reduced the number of allowances grandfathered to other sectors following introductory periods. Consequently, we consider cases where, beginning in 2015, (a) 50% of aviation benchmark allowances are grandfathered, and (b) aviation receives no free allowances.

Changes in average profit margins for alternative allowance allocation assumptions and our base case, which assumes that 85% of allowances are grandfathered each year after 2015, are displayed in Figure 2. Airlines have to purchase more allowances when fewer allowances are grandfathered, which reduces profit margins in all scenarios. The largest decrease in profits is in the ABSORB scenario, but the average profit margin is still positive. However, 2012-2020 average profit margins mask important annual variations. In the ABSORB scenario, profit margins decrease to 1.03% by 2020 when 50% of allowances are grandfathered, and are negative (-0.06%) in 2020 when all allowances are auctioned. Profits are always positive in the FULL scenario as grandfathering fewer allowances only erodes windfall gains.

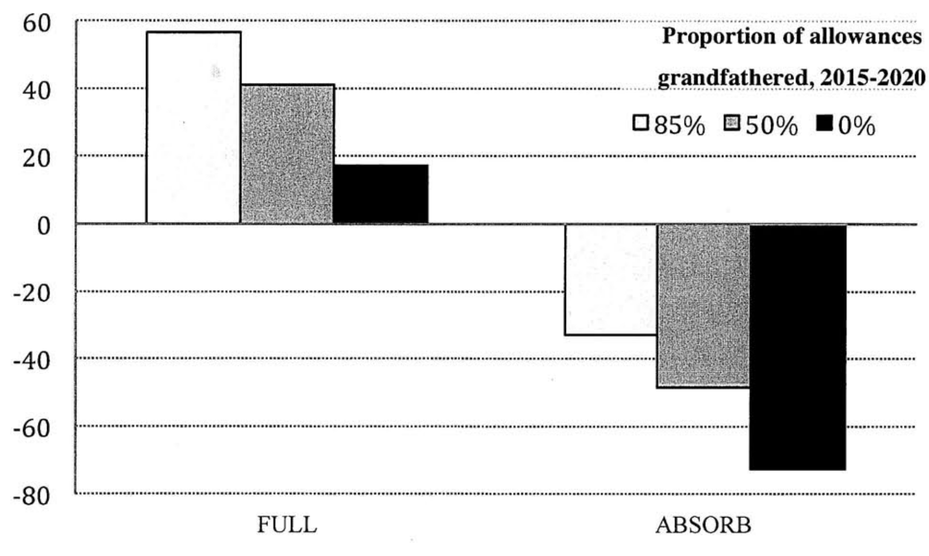

Figure 2. Changes in 2012-2020 average profit margins relative to BaU for alternative allowance allocations, %.

Decreasing the proportion of allowances grandfathered also has a large impact on net transfers from the US to the EU. When all post-2015 allowances are auctioned, net US to EU transfers between 2012 and 2020 are $2.21 billion in the FULL scenario (compared to -1.24 billion when 85% of allowances are grandfathered). The corresponding value in the ABSORB scenario is $3.15 billion (compared to 1.43 billon when 85% of allowances are auctioned).

In another analysis, we examine the sensitivity of our results to the annual improvement in fuel efficiency for new aircraft. In our core scenarios, guided by Lee et al. (2001), we assumed a 1.4% annual improvement in fuel efficiency. We now consider a 1% annual increase in fuel efficiency, as used by US-ICAO/GIACC (2009). When fuel efficiency is lower, airlines have to acquire more CO_2 allowances per flight. Traffic is largest in the ABSORB scenario, so lowering fuel efficiency has the largest impact in this scenario. However, the value of permits purchased between 2012 and 2020 in the ABSORB scenario with lower fuel efficiency is only 2.3% higher than in our core ABSORB scenario. Consequently, a lower increase in fuel efficiency also has a minor impact on profit margins. For example, in the ABSORB scenario, the profit margin for US airlines is 1.97% when the annual increase in fuel efficiency is 1%, compared to 1.98% in our core analysis.

As mentioned above, the share of allowances grandfathered will be based on 2010 market shares in total traffic to, from and within EU-ETS countries. Official market share data had not been released by the European Commission at the time of writing. The 2010 market share of US airlines in total EU-ETS operations derived from APMT-E was 9%, and an estimate from an external data source was 10.2%. To investigate the impact of a higher market share for US airlines on our results, we consider a market share of 11% in a sensitivity analysis.

Increasing the market share of US carriers increases emissions from US airlines in the BaU and the policy scenarios, but has no impact on profit margins in our policy scenarios relative to BaU. This is because the number of free allowances increases with market share-driven increases in emissions. On the other hand, increasing total market share of US airlines has a large impact on international transfers. In the FULL scenario, the 2012-2020 NPV of transfers from the EU to the US is $1.5 billion when the US market share is 11%, 20% higher than when the market share is 9%. The increase in the EU-to-US transfer is driven by larger windfall gains to US airlines. In the ABSORB scenario, US airlines have to purchase more allowances when they have a higher market share, so transfers from the US to the EU are \$1.69 billion, 18% larger than in our core scenario.

2.6 Renewable Jet Fuel Use in the EU-ETS

Under the EU-ETS there is an interesting opportunity for airlines to use renewable jet fuel instead of purchasing EU emissions allowances. In February 2012, the EU released a draft regulation on verification and monitoring of GHGs. Included in the plan are instructions for airlines to report the amount of biomass they use so that biofuels can be accounted as zero emission (European Union, 2012). This regulation is still in draft form and so not European law. However, it raises an interesting question of if and when renewable jet fuel will be cheaper for airlines than EU emissions allowances. In this section I analyze the opportunity for airlines to use renewable jet fuel if this regulation were to become law. In particular, I quantify if, and when, it would be cheaper for airlines to purchase renewable jet fuel as apposed to EU emissions allowances.

It is possible to analytically link the EU emissions allowance price to a price premium of renewable jet fuel relative to conventional jet fuel. The logic being that the carbon price effectively increases the cost of jet fuel per gallon. Renewable jet fuel would also increase the effective cost of jet fuel per gallon. According to Article 38 of the draft regulation, all biomass based renewable jet fuel will be assigned a zero GHG emissions factor. It would be cheaper for airlines to use renewable jet fuel when the effective increase in jet fuel prices is less than the increase from the carbon dioxide price. The relationship described above can be defined analytically. First, the carbon dioxide price would increase jet fuel per gallon by

$$\Delta Jet_{Carbon\ dioxide} = P_{CO2} * K \tag{2.2}$$

where P_{CO2} is the price of carbon dioxide in the EU-ETS, K is equal to the LC-GHG emissions from one gallon of conventional jet fuel and $\Delta Jet_{Carbon\ dioxide}$ is the net increase in jet fuel prices. Next, the increase in the jet fuel price from renewable jet fuel is calculated as equal to the price difference between renewable jet fuel and conventional jet fuel, as shown in equation 2.3.

$$\Delta Jet_{Renewable\ Fuel} = (P_{RF} - P_{CF}) \qquad (2.3)$$

where P_{RF} is the price of renewable jet fuel, P_{CF} is equal to the price of conventional jet fuel and $\Delta Jet_{Renewable\ Fuel}$ is equal to the net increase in jet fuel prices. Therefore it is cheaper for airlines to purchase renewable jet fuel when:

$$\Delta Jet_{Carbon\ dioxide} > \Delta Jet_{Renewable\ Fuel} \qquad (2.4)$$

$$\therefore\ P_{CO2} * K > (P_{RF} - P_{CF}) \qquad (2.5)$$

Equation 2.5 reads that when the price premium of renewable fuel above the petroleum based jet fuel price, (which is comparable to the renewable identification number (RIN) price discussed in appendix I), is less than the emissions allowance price in the EU-ETS multiplied by constant K, it is cheaper for airlines to purchase renewable jet fuel, given appropriate EU policy. Equation 2.5 is plotted in figure 3.

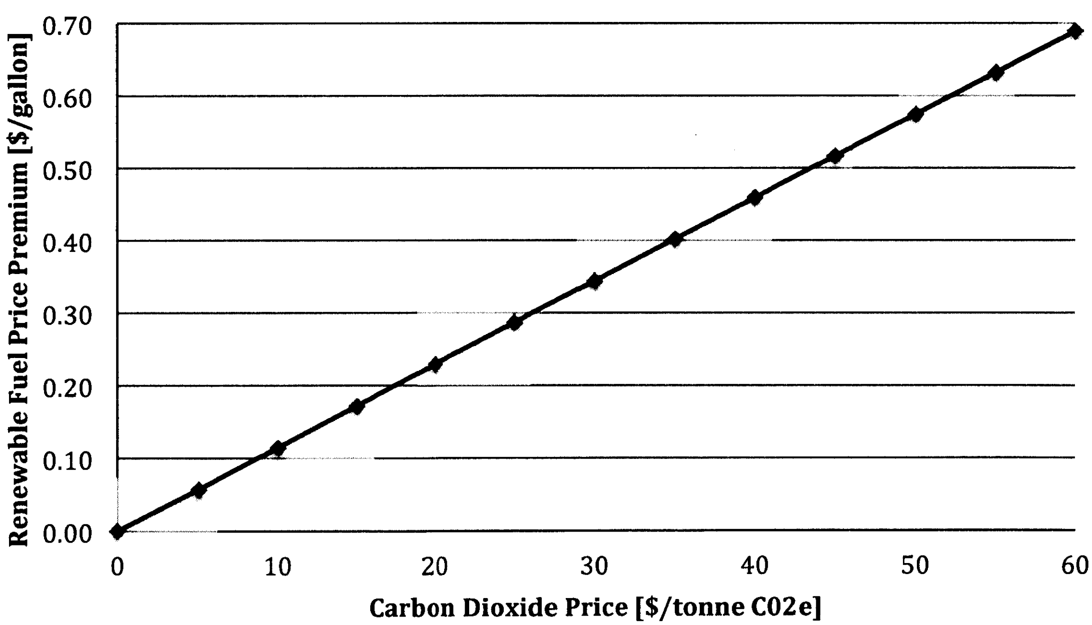

Figure 3. The relationship between allowance price and renewable fuel price premium.

Two conclusions can be drawn from figure 3 and equation 2.5. Firstly, figure 3 shows that with the current allowance price at around \$8/tCO_2 (WSJ, 2012), it is cheaper for airlines to use renewable jet fuel only if it has a price premium of about 10 cents or less. In chapter 3 I review literature and industry estimates of renewable jet fuel. The only commercially available renewable jet fuel in the US at the moment has a price premium of about \$2.70 (Dynamic Fuels 2012). Theoretical estimates fall in a similar and higher range. Therefore it is currently cheaper for airlines to purchase emissions allowances in the EU-ETS than purchase renewable jet fuel. This may change over time as renewable jet fuel decreases in price and EU emissions allowances increase in price.

Secondly, the current white paper EU legislation assigns all biomass based renewable jet fuels a zero emissions factor. Most renewable jet fuels have an emissions factor above 0% (Stratton et al, 2010). This means that renewable jet fuel can have a 40% emissions reduction compared to conventional jet fuel, and be given credit for 100% reduction, resulting in a benefit for the renewable jet fuel industry, and airlines of a 60% factor. Even with this benefit, no renewable jet fuels examined in this thesis are cheaper than emissions allowances. Further, some renewable jet fuels have an emissions factor less than zero. For example switchgrass to F-T with carbon capture and sequestration (Stratton et al., 2010). For these fuels, the price airlines would be willing to pay for renewable jet fuel for a given allowance price would increase slightly.

Given the current EU proposal, equation 2.5 and figure 3 can be used by airlines to determine if it is cheaper to purchase renewable jet fuel or emissions allowances. If the EU changes the legislation and requires emissions factors of renewable jet fuel to be considered, then the renewable jet fuel abatement costs shown table 7 and 8 in this thesis can be directly compared to the EU allowance price. In both cases in is currently cheaper to purchase emissions allowances than the renewable jet fuels shown in table 7 and 8.

It is important to note that the EU white paper legislation in most cases overestimates the societal benefits of renewable jet fuel by giving all fuels a zero emissions factor.

2.7 Conclusions

We evaluated the impact of the EU-ETS on US airlines during the period 2012-2020. Reflecting current market behavior, we considered an emissions price of €15/tCO_2 in

2010 that increased by 4% per year. Under the current market structure on the North Atlantic, we believe airlines will pass on all costs associated with free allowances. On this assumption, airlines received windfall gains valued at $2.6 billion from the grandfathering of allowances, and the cost of the policy was borne by consumers. In our modeling framework, CO_2 emissions from US airlines between 2011 and 2020 increased by 35% in BaU and 32% under the EU-ETS when there is full cost pass-through. The small reduction in aviation emissions reflects high abatement costs in aviation relative to abatement costs in other industries. Results from sensitivity analyses showed that our findings are robust to plausible alternative parameters for key assumptions.

Under proposed EU legislation regarding waiving emissions allowances when renewable jet fuels are used, it is currently cheaper for airlines to purchase EU emissions allowances than renewable jet fuel, even though the EU proposes to assign all biomass based fuels a zero emissions factor.

Finally, this study cannot be used to evaluate the overall effectiveness of including aviation in the EU-ETS. In addition to considering benefits from avoided climate damages, evaluating overall effectiveness would require evaluating economic costs and benefits in all sectors in the economy. This study only considered costs and benefits in the aviation industry.

Chapter 3

3 Estimating Renewable Jet Fuel Abatement Cost Goals and Assessing the Impact of a Hypothetical Renewable Jet Fuel Mandate on US Aviation

3.1 Introduction

The International Air Transport Association (IATA), The International Civil Aviation Association (ICAO) and the Federal Aviation Administration (FAA) have set renewable jet fuel consumption goals for the air transportation industry (IATA 2009, ICAO 2010b FAA 2011). Renewable jet fuel is seen as a way for the airline industry to reduce greenhouse gas (GHG) emissions and reduce fuel price volatility through the development of stable domestic infrastructure (IATA, 2010). In the US, the push for renewable jet fuel arises in the context of major domestic renewable fuels policy, most significantly, the Energy Independence and Security Act of 2007's Renewable Fuels Standard II (RFS2) that mandates 36 billion gallons of renewable fuel per year by 2022 (EISA, 2007). Please refer to Appendix I for a comprehensive description of the mechanics of the RFS2. Under RFS2, only gasoline and diesel fuel have mandated blend ratios. Although producers and blenders can receive credit[7] for making renewable jet fuel, there are no mandated blend ratios for obligated parties (refineries and importers of petroleum based fuel) (EPA, 2010). Given the current higher cost of producing renewable diesels, of which jet fuel is a subset, (Pearlson, 2011), without mandated production quantities or other incentives, economic theory suggests it is unlikely airlines will willingly purchase more expensive renewable jet fuel. In this chapter I explore the impact of such a hypothetical mandate on the US airline industry. The impact and greenhouse gas (GHG) emissions savings of a renewable jet fuel mandate would be significantly dependent on the production cost and lifecycle greenhouse gas (LC-GHG) emissions of renewable jet fuel.

[7] In the form of the value of a Renewable Identification Number, discussed below.

In section 3.2 I review literature and industry estimates of cost and LC-GHG. Moreover, I develop an analytic relationship between renewable jet fuel cost premium and LC-GHG emissions reduction. I use this equation to relate estimates of the social cost of carbon (SCC) to cost premium goals of renewable jet fuel. I use the literature and industry estimates of renewable jet fuel cost premiums to compare the above goals to the current status of the industry. Finally I compare the abatement cost of several renewable jet fuel production pathways to each other and the SCC.

In section 3.3 I use the range of literature and industry estimates from section 3.2 to develop a heuristic model of a renewable jet fuel mandate. In section 3.3.1 I investigate what a reference, or business-as-usual scenario might look like in terms of renewable jet fuel production. In section 3.3.2 I investigate the impacts of a renewable jet fuel mandate.

The existing literature deals extensively with cost and environmental impacts of renewable jet fuels such as Stratton et al. (2010), Hileman et al. (2009, 2010, 2011), Pearlson (2011) and IATA (2009, 2010). Section 3.2 adds to the literature by relating renewable jet fuel GHG abatement cost to renewable jet fuel cost premiums and LC-GHG emissions reduction. While other studies have looked into the GHG abatement cost of corn ethanol and biodiesel (DEFRA, 2008) and the GHG abatement cost to taxpayers of ethanol and biodiesel renewable fuel tax credits (CBO, 2010), this section relates GHG abatement cost of current renewable jet fuels. Further, this section adds to the literature by using the SCC to estimate goals for renewable jet fuel cost premiums for different renewable fuel production pathways. This knowledge could be used by industry, airlines and policy makers to estimate fuel cost premium goals. Section 3.3 presents the first analysis of a renewable jet fuel mandate. This section also adds to the literature on comparing fatty acid methyl ester (FAME) and hydro-processed esters and fatty acids (HEFA). In particular a biodiesel blend wall is calculated. A blend wall is a production limit on renewable fuel, which occurs because when a fuel cannot be used in its pure form (100% blend ratio) in an engine. Below I provide a brief background on jet fuel and renewable jet fuel technology. For a more complete discussion see Hileman et al. (2009), UOP (2005), or Maurice et al. (2001).

3.1.1 Jet Fuel Technology

The dominant fuel used by commercial aviation is a petroleum-based liquid fuel called Jet-A (EIA, 2011). Petroleum, or crude oil, consists primarily of carbon and hydrogen, and contains traces of nitrogen, oxygen, sulfur and metals (Maurice et al., 2001). Crude oil is usually processed into a variety of products including gasoline, jet fuel and diesel. The primary difference between these products is their carbon chain length, as shown in figure 4. It is important to note that jet fuel falls within part of the range of diesel fuel, and so can be used interchangeably as jet fuel and diesel. This has implications for use under the RFS2, which I will discuss below.

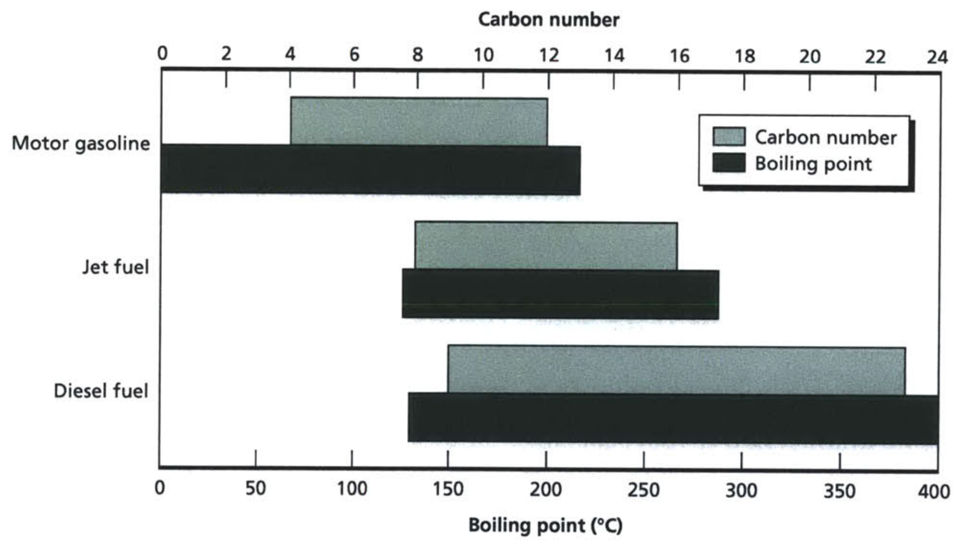

Figure 4. Typical distillation ranges and carbon-number ranges for fuels (Hileman et. al., 2009).

In 2010 the US consumed approximately 20 million barrels of oil products per day, of which about 9% or 1.9 million barrels was used by the airline industry. While currently nearly all-commercial aircraft use petroleum based jet fuel, there is growing interest in renewable jet fuels as a way to reduce aviation GHG emissions and decrease fuel price volatility (IATA 2009, ICAO 2010b FAA 2011). The environmental benefits of renewable fuel are derived primarily from reductions in lifecycle-greenhouse gas (LC-GHG) emissions as well as reductions in particulate matter (PM), hydrocarbons (HC) and carbon monoxide (CO). Reduction in LC-GHG emissions is derived because renewable fuels use biomass as their source of chemical origin with plants absorbing carbon dioxide from the atmosphere through photosynthesis.

In terms of renewable jet fuel use, an important distinction is whether the fuel can be used with current infrastructure, or whether it requires changes to engine technology and distribution systems. Fuel that can be used with current infrastructure is termed *drop-in* renewable fuel (Hileman et al., 2009). These fuels have the same or very similar chemical properties to petroleum based jet fuels. Examples of renewable fuels that require large changes to existing infrastructure include biodiesel, liquid hydrogen and liquid natural gas, as used by the Russian Tu-155 (Tupolev, 2007). In this thesis I focus on drop-in aviation fuels. However, I consider the important interactions between certain drop-in fuels such as HEFA and non-drop-in fuels such as biodiesel.

Below, I briefly outline the technology behind two near term renewable jet fuels, HEFA and BTL via F-T. Other potential renewable jet fuels include sugar-to-jet fuels and fuel from pyrolysis oils. Please see Hileman et al. (2009, 2011), UOP (2005) or Maurice et al. (2001), for a more comprehensive list of near term fuels.

3.1.1.1 Fischer-Tropsch (F-T) Synthetic Fuels from Biomass and Coal

Diesel, drop-in jet fuel and naphtha can be produced by vaporizing coal and converting the gas into synthetic liquid fuels through the Fischer-Tropsch (F-T) process. To make renewable fuel with reduced GHG emissions, it is possible to add biomass to the coal before vaporizing in a process dubbed by Hileman et al. (2009) as biomass-to-liquid (BTL). A 50% blend of F-T synthetic fuel is currently used by O.R. Tambo International Airport in Johannesburg for commercial aviation use (Sasol, 2011).

3.1.1.2 Hydroprocessed Esters and Fatty Acids (HEFA)

Renewable oil (vegetable oils, animal fat, waste grease and algae oil) can be processed using hydrogen treatment (hydroprocessing) to yield a fuel in distillation range of jet fuel, diesel and naphtha (Pearlson, 2011, UOP, 2005). HEFA diesel and jet fuel is similar to F-T synthetic fuel in that it is a drop-in fuel. HEFA meets the requirements of ASTM D975, or diesel fuel. On July 1 2011, ASTM approved the jet fuel product slate of HEFA under alternative fuel specification D7566, (ASTM, 2011). HEFA fuel that meets the D7566 specification can be mixed with Jet-A, up to a blend ratio of 50%. Since the certification of HEFA in 2011, eleven airlines performed commercial passenger flights with blends of up to 50% biojet from used cooking oil, jatropha, camelina and algae. Airlines involved include Finnair, Interjet, Aeroméxico, Iberia, Air France, United and Air China as well as KLM, Lufthansa, Thomson Airways and Alaska Airlines who have done longer series of regular renewable jet fuel flights (IATA, 2012). Having briefly introduced near term renewable jet fuel options, I will now discuss their production cost, LC-GHG emissions reduction and GHG abatement cost in detail.

3.2 Renewable Jet Fuel Life-Cycle Greenhouse Gas Abatement Cost Goals

In this section I develop an analytic relationship between renewable jet fuel cost premium and LC-GHG emissions reduction. I use this equation to relate estimates of the social cost of carbon (SCC) to cost premium goals of renewable jet fuel. I also review literature and industry estimates of renewable jet fuel cost premiums to compare the above goals to the current status of the industry. Finally I directly compare the abatement cost of several renewable jet fuel production pathways to each other and the SCC.

3.2.1 An equation for renewable jet fuel greenhouse gas abatement cost

Following Methodology from CBO (2010) and DEFRA (2008), I derive an equation for the GHG abatement cost of renewable jet fuel. In general terms, the GHG abatement cost is the cost to abate one tonne of GHG. GHG abatement cost can be expressed as the cost premium of renewable jet fuel above conventional jet fuel, divided by the GHG abatement of the renewable jet fuel compared to conventional fuel. This relationship is shown in equation 3.1 where x designates a given renewable fuel type[8].

$$GHG_{abatement\ cost,x} = \frac{Cost\ Premium_x\ [\$/gallon]}{GHG_{abatement,x}\ [tonne/gallon]} \tag{3.1}$$

The cost premium of a type of renewable fuel per gallon, shown in equation 3.2, is the difference between the price of conventional jet fuel and the price of the renewable jet fuel

[8] A renewable jet fuel type designates the combination of feedstock type, production process and land use change scenario (Stratton et al., 2010 and EPA, 2012c).

$$Cost\ Premum_x = \Delta Cost_x = P_{ren,x} - P_{jet} \tag{3.2}$$

where $P_{ren,x}$ is the price of renewable jet fuel of a given type (feedstock and production process combination) and P_{jet} is the price of conventional jet fuel. For a given fuel type, the denominator of equation 3.1 is equal the LC-GHG emissions per gallon of conventional jet fuel per gallon, minus the LC-GHG emissions per gallon of renewable jet fuel as shown in equation 3.3.

$$GHG_{abatement,x} = tCO_2e/gallon_{conventional\ jet\ fuel} - tCO_2e/gallon_{renewable\ jet\ fuel,x} \tag{3.3}$$

LC-GHG emissions per gallon of fuel are taken from Stratton et al. (2010) who report emissions in grams of carbon dioxide-equivalent per mega joule, gCO_2e/MJ, for 26 fuel production pathways/feedstock combinations. $CO_2equivalent$ or CO_2e is equal to GHG emissions from physical extraction (well) to the aircraft (tank) plus GHG emissions during engine combustion, as shown in equation 3.4.

$$\mathrm{CO_2e} = \left(\mathrm{CO_2} + \mathrm{GWP_{CH_4}} \cdot \mathrm{CH_4} + \mathrm{GWP_{N_2O}} \cdot \mathrm{N_2O}\right)_{\text{well-to-tank}} + \left(\mathrm{CO_2}\right)_{\text{tank-to-wake}} \tag{3.4}$$

Grams of carbon dioxide per mega joule, gCO_2e/MJ can be converted to metric tonnes of carbon dioxide per gallon, $tCO2e/gallon$, for different fuel types by using a conversion factor of mega joules per liter, MJ/l, for different fuels found in Hileman et al (2010). I use a constant conversion factor of ~3.79 to convert liters to gallons and divide by 10^6 to convert grams to tonnes, as shown in equation 3.5.

$$[tCO_2e/gallon_{fuel\ x}] = \left[\frac{gCO_2e}{MJ}\right]_{fuel\ X} .* \left[\frac{MJ}{l}\right]_{fuel\ X} * \left[\frac{3.79}{10^6}\right] \tag{3.5}$$

Equation 3.1 can then be rewritten as

$$GHG_{abatement\ cost,x} = \frac{\Delta Cost_x}{tCO_2e/gallon_{conventional\ jet\ fuel} - tCO_2e/gallon_{renewable\ jet\ fuel,x}} \tag{3.6}$$

Dividing equation 3.6 by the LC-GHG emissions of conventional jet fuel yields

$$GHG_{abatement\ cost} = \frac{\Delta Cost_x}{tCO_2e/gallon_{conventional\ jet\ fuel} * \left(1 - \frac{\frac{tCO_2e}{gallon}_{renewable\ jet\ fuel,x}}{\frac{tCO_2e}{gallon}_{conventional\ jet\ fuel}}\right)} \quad (3.7)$$

Where $\frac{\frac{tCO_2e}{gallon}_{renewable\ jet\ fuel}}{\frac{tCO_2e}{gallon}_{conventional\ jet\ fuel}}$ is a metric of normalized GHG emissions of a renewable jet fuel type relative to conventional jet fuel, and is written as ΔGHG_x. In this work I use an average value of conventional jet fuel LC-GHG emissions from Stratton et al. (2010) of about 0.011 tCO_2e/gallon (87.5g CO_2e/MJ). I name this variable *K*. Stratton finds that *K* varies between 80.7 $gCO2_e$/MJ for jet fuel from US crude oil, and 109.3 $gCO2_e$/MJ for jet fuel from hydroprocessed Nigerian crude oil (see Stratton et al. (2010), Table 8, page 14). In a study done by the National Energy and Technology Laboratory (NETL) (Skone, 2008), LC-GHG emissions of conventional jet fuel were found to be 88.0 $gCO2_e$/MJ. This variance in LC-GHG emissions per MJ has a small linear impact on *K*. Following Stratton et al. (2010), I use the baseline value of *K* as the reference value. Using the metrics defined above, equation 3.7 can be rewritten as:

$$GHG_{abatement\ cost,x}[\$/tC0_2e] = \frac{\Delta Cost_x}{K*(1-\Delta GHG_x)}, \quad (3.8)$$

3.2.2 The Social Cost of Carbon, Renewable Jet Fuel Premium and LC-GHG emissions

In the US, Executive Order 12866 requires agencies "to assess both the costs and the benefits of the intended regulation" (IWG, 2010). Renewable jet fuels currently have a higher cost than conventional jet fuels (Dynamic Fuels, 2012), and therefore the benefits need to be assessed in relation to the cost. Societal benefits from renewable jet fuel are derived primarily from abatement in GHG emissions compared to conventional fuel. Their higher cost implies a cost of abatement. As long as renewable jet fuels are more expensive than conventional jet fuel, there will be such a cost of abatement. To compare the cost of GHG abatement of renewable jet fuels to societal benefits derived from GHG abatement, the EPA recommends comparing abatement cost to the Social Cost of Carbon (IWG, 2010) or the cost to society of climate change damage. While SCC refers solely to carbon (in the form of carbon dioxide), many recent estimates, and the estimates I use, use the term SCC but refer to all greenhouse gas emissions. IPCC (2007b) defines SCC as "an estimate of the economic value of the extra (or marginal) impact caused by the emission of one more tonne of carbon (in the form of carbon dioxide) at any point in time". The SCC can be understood as an estimate of the monetized damages associated with an incremental increase in carbon emissions in a given year. SCC can therefore be used to monetize and quantify benefits from avoided GHG emissions.

Estimating the SCC generally involves assigning a monetary value to all impacts of a tonne of GHG emitted in the present, taking into account atmospheric residence time and discounting to the year of emission (IPCC, 2007b). The SCC is intended to include both economic and natural damages such as changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services due to climate change (IWG, 2010).

There is great uncertainty in estimating future climate activity, future economic activity, and relating future costs to present value. The IPCC (2007b) acknowledges that high uncertainties such as "climate sensitivity, response lags, discount rates, the treatment of equity, the valuation of economic and non-economic impacts, and the treatment of possible catastrophic losses" remain. Downing et al. (2005) reported that a survey of fourteen experts in estimating the SCC rated their estimates as low confidence, due to the many gaps in the coverage of impacts and valuation studies, uncertainties in projected climate change, choices in the decision framework and the applied discount rate.

Tol (2003) estimates the SCC using 88 estimates of the marginal costs of carbon dioxide emissions from 22 published studies, combined to form a probability density function. He found the mode at \$5/tC, the mean at \$104/tC, and the 95 percentile at \$446/tC. (1\$/tCO_2, 30\$/tCO_2 and 127 \$/tCO_2 respectively[9]). Tol (2005) updated this range to 14–350 US\$/tC (4–95 US\$/tCO_2) (median and 95th percentile estimates). The

[9] The SCC is reported either as the cost per metric ton of carbon emissions or the cost per metric ton of carbon dioxide emissions. The multiplier for translating between mass of CO_2 and the mass of carbon is 3.67 (the molecular weight of CO_2 divided by the molecular weight of carbon = 44/12 =3.67).

IPCC's most recent report on the SCC from Climate Change 2007: Working Group III: Mitigation of Climate Change uses the Tol (2005) values of between 4 and 95 US$/t$CO_2$. (Stern, 2007), reports a SCC of US$304/tC (US$85/tCO_2) using the PAGE model[10].

As stated above, in the US, Executive Order 12866 requires US agencies "to assess both the costs and the benefits of the intended regulation" (IWG, 2010). The EPA presents the SCC in the 2010 US Government Interagency Report (IWG, 2010) to allow agencies to incorporate the social benefits of reducing carbon dioxide emissions. EPA relies on three most frequently cited integrated assessment model (IAMs) to estimate the SCC: FUND, DICE and PAGE[11] EPA results for 2010 indicate values of the SCC at between 4.7$/t$CO_2$ and 64.9$/t$CO_2$, with values rising as high as $136.2/t$CO_2$ by 2050 (IWG, 2010).

More recent estimates of the SCC are 100$/t$CO_2$ (Hope, 2011) and $128/t$CO_2$ (Pycroft, 2011). Pycroft also gives a range of $5 - $564 (5-95th percentiles).

For the purposes of this thesis, I use a range of values for the SCC of $25/t$CO_2$e as a low estimate, $100/t$CO_2$e as a mid range estimate and 175$/t$CO_2$e as a high estimate. I choose this range to take account of the current uncertainty in SCC and mitigation cost estimates, with most estimates having a skewed probability density function (with a higher probability of values of SCC greater than the mode) (IWG, 2010), the upward trend of the majority of SCC estimates[12] and taking into account these estimates will be updated as the science and economics of climate change develops.

In the next section I use equation 3.8 to relate the SCC to literature and industry estimates of renewable fuel price premium for different fuel LC-GHG emissions reductions. I then estimate theoretical price premium goals for different fuel LC-GHG emissions reductions.

[10] The PAGE (Policy Analysis of the Greenhouse Effect) model by Chris Hope (Hope, 2008)

[11] The DICE (Dynamic Integrated Climate and Economy) by William Nordhaus (e.g. Nordhaus et al. 2000), The FUND (Climate Framework for Uncertainty, Negotiation, and Distribution) model, by Richard Tol (e.g. Tol, 2006).

[12] In general, SCC over time tends to increase since future emissions could create larger incremental damage with physical and economic systems becoming more stressed (IWG, 2008)

3.2.3 Deriving Renewable Jet Fuel Cost Premium Goals Using the Social Cost of Carbon

As stated above, I use the SCC as an estimate of the benefits of avoided GHG emissions. In this section I relate the SCC to the cost of renewable jet fuel production. Using this relationship, it is possible to define goals for different types of renewable jet fuel cost premium over conventional jet fuel, the aim for the industry, policy makers and airlines being that the GHG abatement cost of fuel type x is less than or equal to the SCC. This can be written as shown in equation 3.9.

$$GHG_{abatement\ cost,x}\ [\$/tCO2e]\ \leq SCC\ [\$/tCO2e] \tag{3.9}$$

For fuels that have well quantified LC-GHG emissions reduction, equation 3.9 can be rearranged to relate the SCC and the fuel's LC-GHG emissions reduction to the fuel's cost-effective cost premium. Here cost-effective means that the higher cost of the renewable fuel offsets future avoided climate damages because of the fuel's lower LC-GHG emissions compared to conventional jet fuel. Therefore from a societal perspective, the extra cost of the renewable jet fuel is cost-effective if the following conditions are met:

$$GHG_{abatement\ cost,x}\ \leq SCC$$

$$\therefore \Delta Cost_x \leq SCC * K * (1 - \Delta GHG_x) \tag{3.10}$$

Equation 3.10 links the GHG abatement cost and SCC to the cost premium and LC-GHG emissions of a renewable fuel. The equation forms a three dimensional space, with a linear relationship between abatement cost and renewable fuel price premium, and a hyperbolic relationship between abatement cost and LC-GHG emissions reduction normalized to conventional jet fuel. Figure 5 shows equation 3.8 in two dimensions, for different values of ΔGHG_x. Additionally, SCC estimates are plotted.

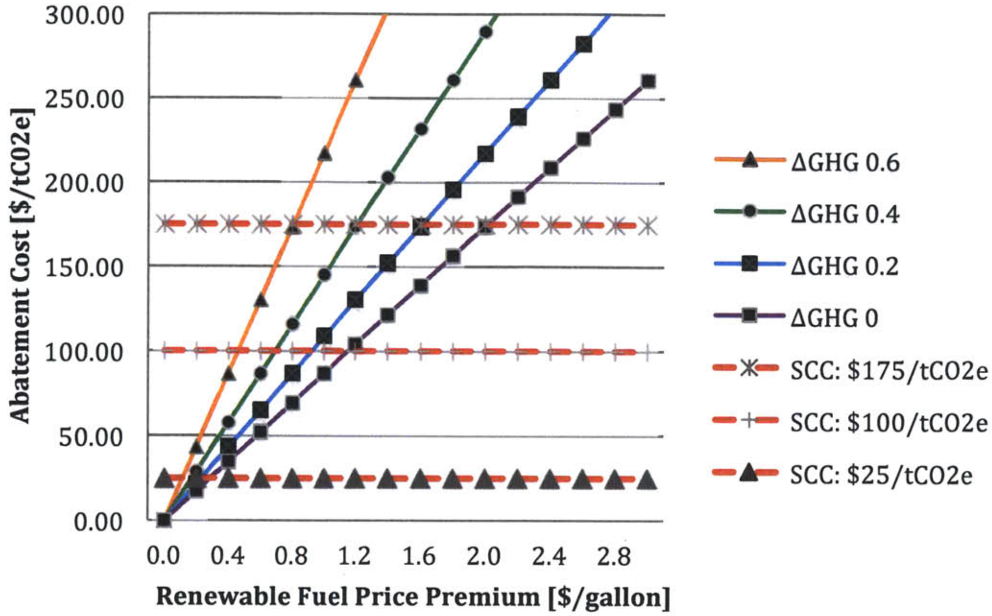

Figure 5. GHG abatement cost as a function of renewable fuel price premium for different ΔGHG .

ΔGHG_x values of between 0 (100% life cycle reduction) and 0.6 (40% reduction) were chosen. This range approximately represents the range of fuels identified by Stratton et al. (2010) that have a baseline LC-GHG emissions reduction less than conventional jet fuel. Moreover, the upper bound falls close to the RFS2 classification of advanced biofuel, the category under which renewable jet fuel falls (EISA, 2007).

Using the estimates of low, average and high SCC discussed above, figure 5 or equation 3.10, can be used to estimate theoretical renewable jet fuel cost premium goals for different LC-GHG emissions reductions. For example, using the average SCC of 100\$/tCO_2e, the renewable jet fuel cost-effective cost premium (taking into account the societal damages of GHG emissions), ranges between 40 cents and \$1.2, depending on selected LC-GHG reductions. For a \$200/tCO_2e SCC, the range increases to between \$1 and \$2.40. In other words for a renewable jet fuel, such as soy oil to HEFA renewable jet fuel, which has an estimated LC-GHG emissions reduction of ~60% for a no-land-use change scenario (Stratton et al., 2010) the renewable jet fuel could be between 20 cents and \$1.4 more expensive than conventional jet fuel, and still be cost-effective from a societal perspective.

Equation 3.10 and figure 5 represents the generalized relationship between renewable jet fuel cost premium, LC-GHG reductions and the SCC. As knowledge of these three variables improves, equation 3.10 can be used to re-evaluate cost-effective renewable jet fuel options.

3.2.4 Estimating renewable jet fuel cost premium goals using the SCC

In this section I use SCC estimates and renewable jet fuel LC-GHG emissions from Stratton et al. (2010) and Carter (forthcoming) to calculate cost-premium goals for different renewable jet fuel pathways. I compare theses goals to current literature and industry cost estimates of renewable jet fuel as an indication of where the industry should be aiming for mature cost-effective renewable jet fuel production. I also calculate the GHG abatement cost of renewable jet fuel pathways that have both cost and LC-GHG emissions reduction estimates publicly available.

Equation 3.10 can be solved for specific estimates of renewable jet fuel LC-GHG emissions and SCC. The value obtained, $\Delta Cost_x$, indicates the cost-effective cost premium for renewable jet fuel type x. I use LC-GHG emissions estimates from Stratton et al. (2010) for 26 renewable jet fuel feedstock/ production/ land-use-change (LUC) combinations. I use estimates from Carter (forthcoming) for LC-GHG estimates of algae from 'Open Pond Wet' and 'Flat Panel Wet', the two production pathways identified by Carter that have LC-GHG emissions less than conventional jet fuel.

Stratton et al. (2010) list 'low', 'baseline' and 'high' LC-GHG estimates for each renewable jet fuel production/feedstock combination as well as for conventional jet fuel. The three values are based on well-to-wake[13] emissions, and exclude LUC factors. LUC is taken into account for different production/feedstock combinations with a unique estimate for each LUC scenario. Table 4 (from Stratton et al. (2010)) shows assumptions made for each LUC scenario.

[13] Where well-to-wake refers to GHG emissions from extraction to aircraft tank, plus combustion emissions.

Table 4. Land use change scenarios (Stratton et al., 2010, pg 96).

Land use change	Scenario 0	Scenario 1	Scenario 2	Scenario 3
Switchgrass	None	Carbon depleted soils converted to switchgrass cultivation	n/a	n/a
Soy oil	None	Grassland conversion to soybean field	Tropical rainforest conversion to soybean field	n/a
Palm oil	None	Logged over forest conversion to palm plantation field	Tropical rainforest conversion to palm plantation field	Peat land rainforest conversion to palm plantation field
Rapeseed oil	None	Set-aside land converted to rapeseed cultivation	n/a	n/a
Salicornia	None	Desert land converted to salicornia cultivation field	n/a	n/a

Similarly, Carter (forthcoming) gives a 'baseline', 'negative error' and 'positive error' for each algae fuel LC-GHG emissions estimates. For a given SCC estimate, a cost premium goal is calculated using equation 3.10. Results are plotted in figure 6. Baseline values (shown by the red point) are calculated using baseline LC-GHG emissions for conventional jet fuel and renewable jet fuel. The error bars represent high and low estimates of renewable jet fuel LC-GHG emissions compared to baseline conventional jet fuel LC-GHG emissions (following Stratton et al. (2010)). I use the medium SCC value of \$100/tCO_2e for all figure 6 estimates (for the full range of combinations, please see appendix I).

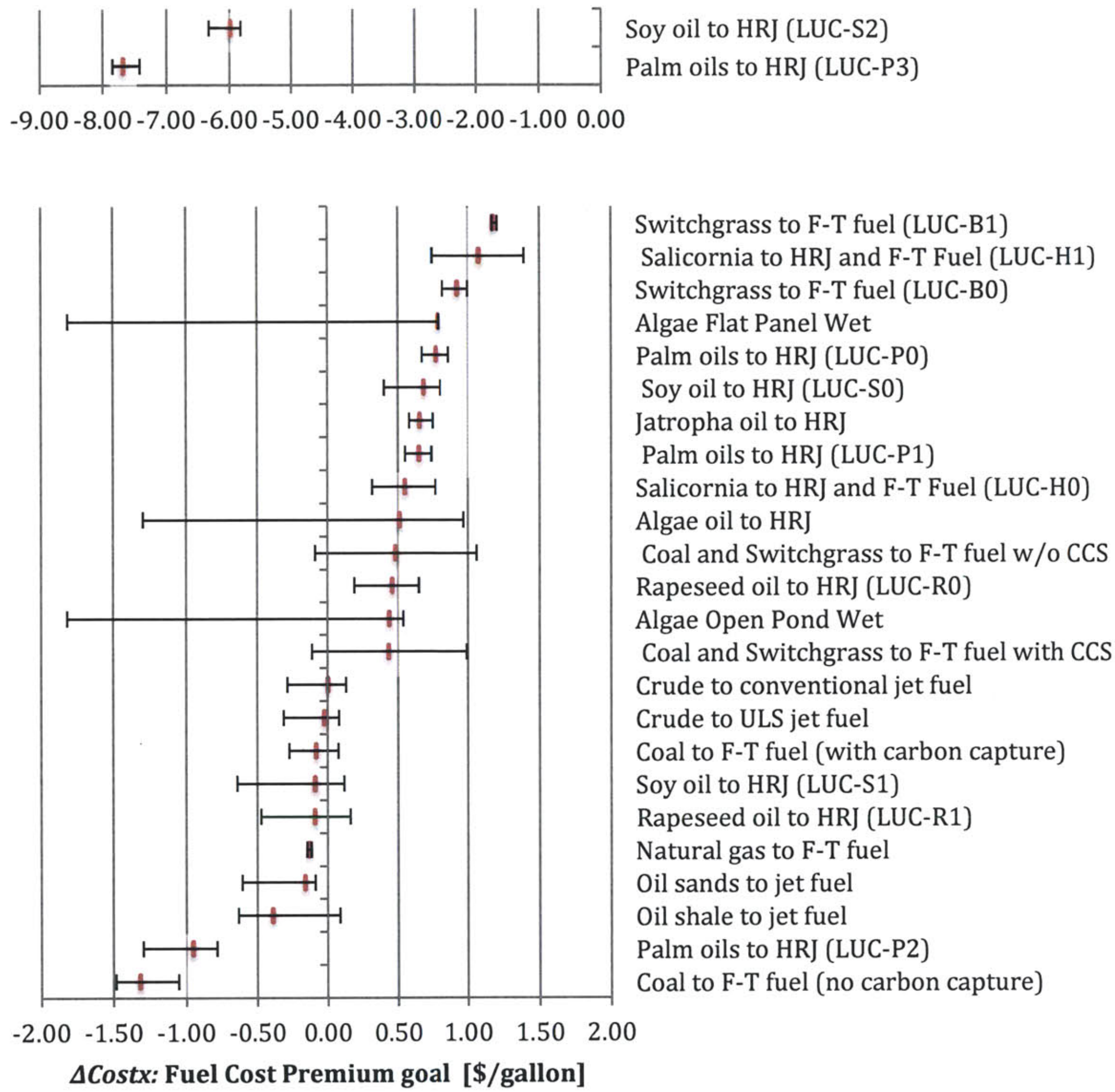

Figure 6. Societal Cost-Effective Renewable Jet Fuel Cost Premium Goals.

Figure 6 shows the results of applying equation 3.10 to the Stratton et al. (2010) and Carter (forthcoming) estimates. Cost premium goals range from about negative $8 for Palm oils to HRJ (LUC-P3) to about a $1.50 premium for Switchgrass to F-T fuel (LUC-B1). Negative values indicate that LC-GHG emissions are higher than conventional jet fuel. Therefore, in terms of the SCC, these fuels need to be cheaper than conventional jet fuel because of damages from extra GHG emissions. Positive cost premium values indicate fuels that have a savings in GHG emissions, and therefore can be more expensive than conventional jet fuel and still be cost-effective from a societal perspective. Large error bar values indicate high levels of uncertainty in GHG emissions. Renewable fuel producers, airlines and policy makers can use figure 6 to determine renewable jet fuel cost premium goals.

It is possible to compare the goals shown in figure 6 to current renewable jet fuel price estimates from the literature and industry. Such a comparison needs to be interpreted carefully given the infancy of the renewable jet fuel industry, and the paucity of renewable jet fuel price estimates. However, the estimates provide a starting point for assessing the current cost-effectiveness of the renewable jet fuel industry. All assumptions are noted. Theoretical cost estimates are taken from Pearlson (2011) for HEFA from soy oil, Bredehoeft et al. (2011) for biomass to liquid (BTL) via F-T, and Carter (forthcoming) for HEFA from algae oil. Please note that Carter's algae to HEFA numbers take into account all capital and operating expenses but do not include a return on investment, as modeled in Pearlson's soy oil to HEFA numbers. The inclusion of a return on investment would marginally increase the price reported in figure 7. Pearlson uses five-year average feedstock prices to a estimate baseline soy to HEFA price. Feedstock cost makes up the majority of Pearlson's estimates. I therefore use five year average conventional jet fuel prices from EIA (2012). This estimate is shown in table 5 below. I estimate the cost premium of soy to HEFA based on current feedstock prices and the current price of conventional jet fuel using linear interpolation from results in table 6.7, page 75 of Pearlson (2011). This value is shown in figure 7. Industry prices are taken from the only current commercial US producer of renewable jet fuel, Dynamic Fuels (2012) for HEFA from animal fat based on average quarter 3 2011 prices. I include the price of soy methyl ester biodiesel over the same period for comparative purposes. Table 5 and 6 outline source and assumptions for each price.

Table 5. Literature Price Estimates: Assumptions and Sources.

Pathway	Economic Source	Price Assumption	Delta LC-GHG Source
Soy to HEFA (feedstock 5 year average)	Pearlson, 2011	5 year average: soybean oil price ($2.62), jet fuel price ($2.25)	Stratton (2010), LUC S0
Soy to HEFA (feedstock current)	Pearlson, 2011, Worldbank,	2012 for soybean oil price 4/2012 of $4.29/gallon	Stratton (2010), LUC S0
Biomass-to-liquid via F-T	Bredehoeft, 2011		Stratton (2010),
Algae Open Pond Wet	Carter, Forthcoming		Carter, Forthcoming
Algae Flat Panel Wet	Carter, Forthcoming		Carter, Forthcoming

Table 6. Industry Price Estimates: Assumptions and Sources.

Pathway	Price Source	Price Assumption	Delta LC-GHG Source
SME Biodiesel	Dynamic Fuels, 2012	Q3 2011 Average	EPA, 2012
Animal Fat to HEFA	Dynamic Fuels, 2012	Q3 2011 Average	Assume Same as soy HEFA

Cost estimates from sources shown in table 5 and 6 are plotted in figure 7, shown by the green marks. Cost premium values are relative to the EIA Annual Energy Outlook 2012 reference jet fuel value of $3.08/gallon (EIA, 2012b). Only baseline values are used. Please refer to appendix III for a range of estimates. It is important to note that the green marks indicate renewable jet fuel price estimates, whereas the red marks indicate societal cost-effective premiums for renewable jet fuel. Ideally, a renewable jet fuel cost premium (green mark) should be less than or equal to the cost premium indicated by the red marks in figure 6 and 7. Red marks indicate cost premium goals for a $100/tCO_2e$ SCC, as in figure 6. However, in figure 7 high error bars use a $175/tCO_2e$ SCC and low bars use a $25/tCO_2e$ SCC. This extends the range of cost-premium values.

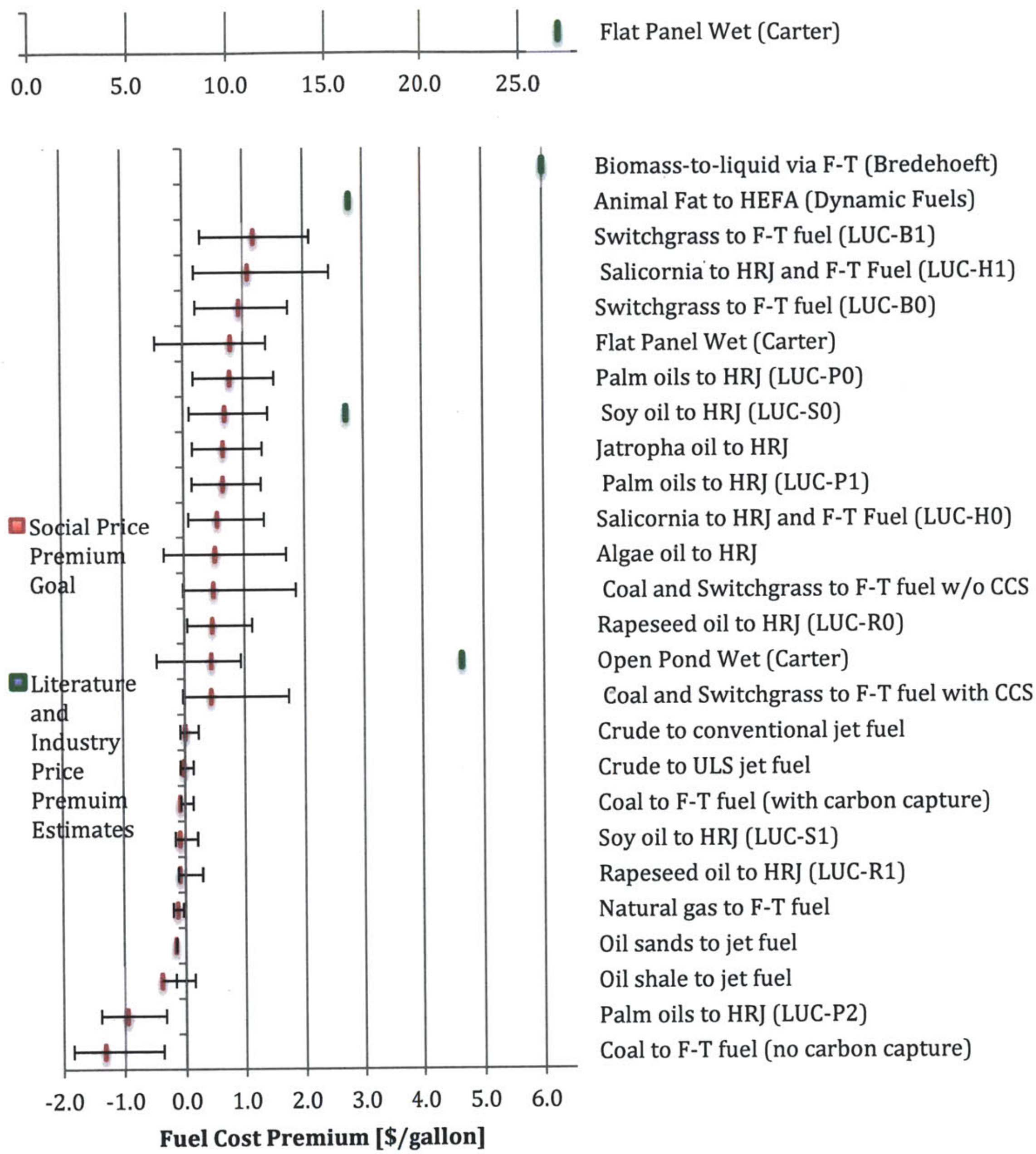

Figure 7. Comparison of Industry and Literature Cost Estimates and Cost Premium Goals.

Figure 7 shows that for the range of SCC between \$25-\$175/tCO_2e, none of the literature or industry prices are cost-effective. This is also shown in section 3.2.5 by directly comparing abatement cost of renewable jet fuels to the SCC. Pearlson's (2011) theoretical estimate of soy oil to HEFA renewable jet fuel using current feedstock prices is the closest estimate to being cost effective. It is important to note that these cost estimates are a snapshot of an emerging renewable jet fuel industry (Dynamic Fuels only began production in late 2010). This means that costs are likely to be reduced over time through learning effects and competition. Figure 7 shows where the industry currently is, and where it should aim as it matures.

3.2.5 Estimating renewable jet fuel GHG abatement costs

By combining literature and industry LC-GHG emissions and cost data estimates, it is possible to use equation 3.8 to derive abatement costs for select renewable jet fuel pathways. As with price estimates shown in figure 6, such estimates should be taken as a very preliminary estimate of renewable jet fuel cost-effectiveness. The estimates and assumptions from table 5 and 6 are used to calculate the baseline abatement costs shown in table 7 and 8 for literature (theoretical) and industry (actual) abatement costs respectively. Please refer to appendix III for a full range of estimate.

Table 7. Literature Estimates Results.

Pathway	Price [$/gal]	Price Premium [$/gal]	Delta LC-GHG	Abatement Cost [$/tCO2e]
Soy to HEFA (feedstock 5 year average)	3.98	1.73	0.41	253.83
Soy to HEFA (feedstock current)	5.78	2.70	0.41	398.16
Biomass-to-liquid via F-T	8.93	5.85	0.19	632.05
Algae Open Pond Wet	7.71	4.63	0.62	1066.54
Algae Flat Panel Wet	30.66	27.58	0.32	3516.92

Table 8. Industry Estimates Results.

Pathway	Price [$/gal]	Price Premium [$/gal]	Delta LC-GHG	Abatement Cost [$/tCO2e]
SME Biodiesel	5.46	2.38	0.5	414.15
Animal Fat to HEFA	5.70	2.62	0.41	384.41

Estimating renewable jet fuel abatement cost in this form allows for direct comparison to the SCC, as well as other estimates of abatement cost such as the carbon price in the EU-ETS (Malina et al. 2012), renewable fuel abatement costs reported by DEFRA (2008) and CBO (2010), US economy abatement costs such as in Morris (2008) and industry abatement cost estimates such as Creyts (2007).

Table 7 and 8 shows that both literature and industry estimates of abatement costs are above the high estimate of SCC at \$175/tCO_2e. Further the abatement costs are far higher than the current abatement cost in the EU-ETS (as shown by the CO_2 allowance price) at approximately $8/t$CO_2$ (WSJ, 2012). This suggests, as discussed above, that it is cheaper for airlines to purchase EU emissions allowances than renewable jet fuel.

These estimates show that as the renewable jet fuel industry matures, it needs to reduce cost premium relative to conventional jet fuel, or increase LC-GHG emissions reductions. It is important to note that given the paucity of renewable jet fuel cost estimates, the infancy of the industry and the uncertainty around the SCC value, table 7 and 8 should be taken as a very preliminary estimate of renewable jet fuel cost-effectiveness.

3.2.6 Conclusion and Discussion

In this section I related renewable jet fuel cost premium and abatement cost to the benefits of avoided climate damage or the SCC. An equation (3.10) was derived to quantify cost premium goals for given LC-GHG emissions. For cost-effective GHG mitigation, the marginal cost of GHG mitigation should be equal to the marginal benefits of emissions reduction (IWG 2010, IPCC 2007b). IPCC (2007b), define the marginal benefits as the avoided damages for an additional tonne of carbon, otherwise known as the social cost of carbon (SCC). Despite uncertainty in analytic results of SCC, it is possible to draw estimate from the literature, which I bound at $25/t$CO_2$e at the low end, $100/t$CO_2$e as a mid-range estimate and $175/t$CO_2$ as a high estimate. I use the SCC to estimate societal cost-effective renewable jet fuel price premiums, shown in figure 6. Values range between 42 cents for Coal and Switchgrass to F-T fuel with carbon capture and sequestration and $1.17 for switchgrass to F-T with carbon depleted soils turned to switchgrass cultivation.

Further, I compare literature and industry estimates of renewable jet fuel price to compare the above goals to current prices. I find that no renewable jet fuel pathways examined are currently cost-effective. I also calculate renewable jet fuel abatement cost, with the same result. These results suggest that the emerging industry (the first plant in the US started production in 2010) must aim to reduce fuel cost, or decrease LC-GHG emissions, as the industry matures. Further, it suggests that it is cheaper for airlines to purchase EU emissions allowances at ~8/tCO_2e than purchase renewable jet fuel with a current abatement cost close to ~\$400/tCO_2e. This result holds irrespective of EU ruling on biomass emissions factor, as discussed in chapter 2.

Calculating the GHG abatement cost of renewable jet fuels also allows for comparison to the CO_2 allowance price in a US emissions trading scheme. Winchester et al. (2011) model the impact of the now defunct Waxman-Markey Bill (H.R. 2454, 2009) on the US airline industry. The chief emissions reduction instrument in H.R. 2454 is a cap-and-trade system that would cover between 85% and 90% of all U.S. emissions. The cap would have been gradually tightened through 2050. It is 80% of 2005 emissions (5.6 gigatons, Gt, of CO2-e) in 2020, 58% (4.2 Gt) in 2030, and 17% (1.2 Gt) in 2050. The CO_2 allowance cost is found to be between \$7.27 and \$22.25/tCO_2e in 2015 depending on whether aviation CO_2 emissions have a multiplicative factor because of the additional impact of high altitude emissions, rising to between \$28.69 and \$87.08/tCO_2e. The conclusion can be drawn that if renewable jet fuels do not get cheaper in terms of abatement cost, it would be cheaper for airlines (and more cost-effective from a societal perspective) to be part of an emissions trading scheme such as H.R. 2454, than purchase renewable jet fuel.

Of course this result is dependent on future renewable jet fuel prices, which are difficult to forecast. For a full analysis of aviation abatement cost options, the above values should be compared to other abatement cost estimates such as Kar (2010) who identifies seven abatement options including: ***Weight*** - reduce the aircraft's empty weight and the payload mass. ***Engine Efficiency*** – reduce the specific fuel consumption by improving the engine efficiency, such as through higher bypass ratios. ***Aerodynamics*** - increase the lift to drag ratio. ***Average Load Factor*** – fill flights with more passengers and cargo. ***Fleet Mix*** - use larger aircraft that take advantage of scale economies to be more efficient on a seat-mile or ton-mile basis. ***Flight Distance*** – modify network topology to reduce connections and improve air traffic control procedures to reduce flight distances. ***Cruise Speed*** – operate at cruise speeds that minimize fuel burn.

Further, it is likely that as the renewable jet fuel industry matures, production costs will decrease. Evidence includes the well-documented *learning effect.* As an industry matures, the average marginal cost of production is expected to decrease. For example, Dynamic Fuels has seen an 84% reduction in operating costs since production began in

2010 (Dynamic Fuels, 2012). Also, the USDA Economic Research Service (ERS, 2011) estimates that by 2017, soy biodiesel will be equal to the cost of conventional diesel. This estimate is based on an increasing petroleum fuel price, and decreasing soy oil prices. This implies that by 2017, soy oil to HEFA will also be a cost effective means of GHG mitigation. Rising petroleum based fuel prices (EIA, 2011) will reduce the price premium of renewable jet fuels, while IPCC estimate that the SCC will grow at about 2.4% p.a. meaning, increasing the benefits of GHG mitigation.

Stern (2007) argues for government intervention when obstacles that hinder the development of low carbon/renewable technologies exist. The extent to which an obstacle of technology development applies to biofuels and justifies a mandate is unclear.

Finally, unlike the EU, where renewable fuel legislation is directly aimed at GHG mitigation, in the US, GHG mitigation is one of many goals, the primary being *Energy Independence and Security,* as well as *agricultural development* (IESA, 2007). For example Oak Ridge National Lab (Leiby, 2007) estimates that benefits of renewable fuel other than GHG abatement range from \$6.71 - \$23.25 \$/barrel or ~30c/gallon.

The above reasons indicate that with investment, some renewable jet fuels could over time be a cost-effective GHG mitigation strategy, and current high costs do not justify nonaction. However, the analysis shows that at current prices and LC-GHG emissions factors, renewable jet fuels still have some way to go before they fall within the range of accepted SCC. Further, the analysis shows that at current renewable jet fuel prices, it is cheaper for airlines to purchase emissions allowances in the EU, or in a emissions trading scheme such as H.R. 2454, than purchase renewable jet fuel.

3.3 The Impact of a renewable jet fuel mandate on US aviation

3.3.1 Introduction

The Renewable Fuels Standard II as legislated in the 2007 Energy Independence and Security Act mandates blending requirements for gasoline and diesel fuels (EISA, 2007). Although never publicly stated, in the future this legislation could theoretically be changed to include blending requirements for jet fuel. The magnitude of such a blending mandate is modeled using renewable jet fuel goals set by the Federal Aviation Administration (FAA), taking into account goals set by the US NAVY and the USAF.

In this section I discuss the impact of a hypothetical jet fuel-blending mandate on the US aviation industry. In section 3.3.2 I discuss certain points of interest for renewable jet fuel production and adoption if no mandate comes online before 2022, a scenario I call reference. In particular I discuss the production of HEFA, which can be used as a renewable jet fuel (UOP, 2005), and biodiesel, which cannot (Hileman et al., 2009), to meet part of the RFS2 mandate. In section 3.3.3 I define and apply a heuristic model to assess the impact of a renewable jet fuel mandate on US aviation.

A plausible, but not necessary, mechanism for mandating the above goals could be implementation through the RFS2 and administration by the US Environmental Protection Agency (EPA)[14]. Another plausible scenario could be cost-effective renewable jet fuel adoption within the framework of an emissions trading scheme. When the GHG abatement cost of renewable jet fuel is less than the CO_2 price, companies would turn to renewable jet fuel as the cheapest option. In this section I focus on a mandate similar to the RFS2, but discuss cost-effective renewable jet fuel adoption in later sections. Please see Appendix I for a detailed description of the RFS2. Obligated parties (refineries and importers of petroleum based fuel) under the new RFS2 would be required to blend gasoline, diesel and jet fuel in proportions determined by the EPA. Renewable Identification Numbers (RINs) are already issued for the production of renewable jet fuel. Obligated parties would be required to purchase either renewable jet fuel with attached RINs or the equivalent number of separated RINs to meet their blending volume obligation. As with the existing RFS2, the price premium for renewable fuel, or RIN price, would presumably be passed from producers to refineries and importers through the mandate. The cost would then be passed through to the consumer (in this case airlines and finally passengers) in the form of increased jet fuel prices[15]. Jet fuel prices per gallon would increase by the RIN price (the price premium of renewable fuel), less any tax credit, multiplied by the blend ratio (where the blend ratio is the mandate in a given year divided by the total jet fuel consumption in that year).

I model the hypothetical jet fuel blending mandate using three published goals: the Federal Aviation Administration (FAA) goal of one billion gallons of renewable jet

[14] Note that there are numerous other forms of implementation, such as a mandate administered outside of the EPA.
[15] Please see Chapter 2 for a detailed discussion of cost pass through behavior.

fuel per year from 2018 onwards, as outlined in the FAA Destination 2025 (FAA, 2011), the USAF goal to cover 50% of USAF domestic aviation via 50:50 alternative fuel blends cost competitive acquisition from domestic sources by 2016 (USAF, 2010) and the US Navy goal to have half of its total energy consumption afloat from alternative sources by 2020 (USNAVY, 2010). It is important to note that the above three goals are all *goals*, and therefore do not *mandate* blending requirements for jet fuel. However, they provide a starting point for this analysis to assess the impact of a renewable jet fuel mandate. The magnitude of the USAF and NAVY goals are shown in figure 9, as reported in Carter et al. (2011).

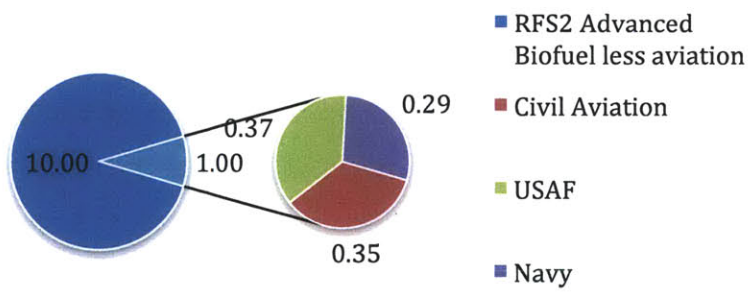

Figure 8. RFS2 Mandated Advanced Biofuel in 2018 [billion gallons] including assumed civil mandate scenario. (Data from Carter et al. 2011)

Based on these estimates, I set up three scenarios, shown in table 6. The first is the 'Reference Scenario'. This scenario is business as usual, or the scenario where no renewable jet fuel mandate is legislated before 2022. The next two scenarios are scenarios where a renewable jet fuel mandate is legislated. There is considerable uncertainty around such a renewable jet fuel mandate: the quantity of the mandate, the types of renewable jet fuels that would be available for airline use, the cost of such fuels and the LC-GHG emissions of such fuels. To take into account the uncertainty around the magnitude of the mandate, I define two scenarios[16]: the Civil Scenario and the Civil Less Military Scenario. In the Civil Scenario, I use the magnitude of the FAA goal of one

[16] The other uncertainties are discussed and modeled in section 3.3.3.

billion gallons of renewable jet fuel per year by 2018 for use by civil aviation. In terms of the FAA goal, which is politically unrelated to any mandate, the stated one billion gallons includes the USAF and the NAVY goals[17]. I therefore assume a second scenario, Civil less Military, in which I use the mandate of the FAA goal, less the magnitude of the estimated NAVY and USAF usage. These estimates are shown in table 6.

Table 9. Scenarios.

Scenario	Civil Aviation Mandate [billion gallons/year]	Start Date
Reference Scenario	0	-
Civil Scenario	1	2018
Civil less Military Scenario	0.33	2018

Below I discuss the reference scenario, before going into the modeling approach and results.

3.3.2 The Reference Scenario

There are numerous renewable jet fuels that could possibly be produced in the next decade. A non-exhaustive list includes HEFA from soy oil, animal fat, jatropha or algae or BTL via F-T from numerous cellulosic sources such as forest residues. See Hileman et al. (2009, 2011), UOP (2007), OECD (2012) and Carter (forthcoming) for a more complete list of possible fuels. All of these fuels could be used as either renewable jet fuel or diesel (depending on the chemical composition of the fuel) under the RFS2, and therefore could theoretically be produced to meet the gasoline and diesel blending mandates (EPA, 2012b). Predicting which of these fuels will be produced under the RFS2 means forecasting legislative factors, loans, costs and competitors, amongst numerous other variables. This makes accurate prediction of which renewable jet fuels will be produced very challenging. However, in the absence of a renewable jet fuel mandate, and with the current higher costs of renewable jet fuel compared to conventional jet fuel (see section 3.2), it is unlikely that renewable jet fuel would be used by airlines, but rather as diesel or gasoline which have mandated blending requirements.

[17] Personal correspondence with the FAA, November 2011.

Nevertheless, I focus on one aspect of a reference scenario: whether HEFA from animal fat (I also consider HEFA from soy oil) is likely to be produced over biodiesel under current legislation. This is an interesting question because HEFA from animal fat is currently the only renewable jet fuel being produced in the US. Dynamic Fuels in Giesmar, Louisiana, began construction in 2007 of a 75 million gallons per year HEFA plant with chicken fat as a feedstock from Tyson Chickens. Construction was completed in 2010 and in 2011 the plant was operating at full capacity (Dynamic Fuels 2012). Further, literature estimates from Pearlson (2011) suggest that HEFA from soy oil is currently estimated to be the lowest cost pathway for renewable jet fuel production. What makes this question more interesting is that biodiesel, or fatty acid methyl ester (FAME) competes with HEFA in the biomass-based diesel category of the RFS2 (these are the only fuels currently being produced in this category), and both these fuels fall under the advanced undifferentiated biofuel category. See Appendix I for more details of this categorization. The question I therefore set out to address is whether FAME or HEFA is likely to be produced in larger quantities under current legislation. Figure 10 shows historic production, imports, exports and consumption of FAME and HEFA in the US.

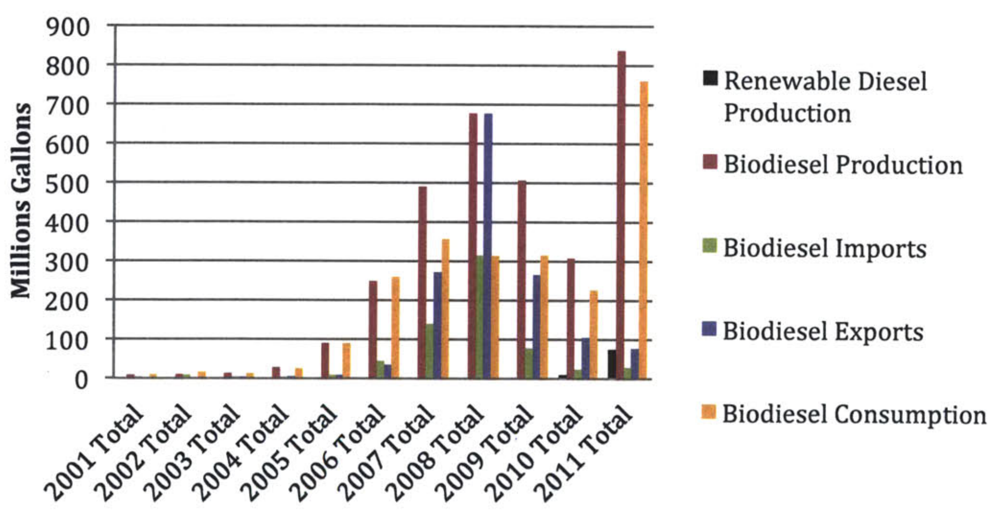

Figure 9. FAME and HEFA in the US (Data from EIA, 2012a).

HEFA also competes with FAME for feedstock (vegetable, plant oils, and waste grease, and in the future algae oil). However, these two fuels have very different production processes and result in very different fuels. FAME is made by reacting fatty acids derived from vegetable oils or animal fat with methanol or ethanol (a short chain mono-alkyl ester) to form esters of long chain fatty acids, and glycerin (used in soap production) through transesterification (Knothe, 2010), while HEFA is made through hydroprocessing (UOP, 2005). These two processes are depicted in the flowchart in figure 11.

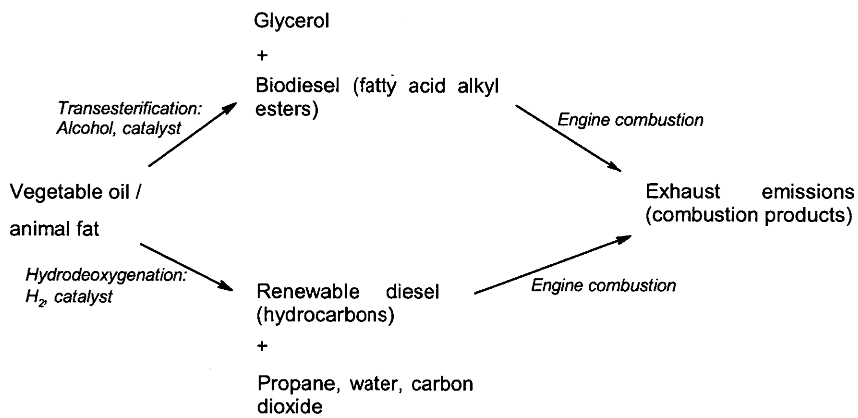

Figure 10. Flow chart for transformation of lipid materials to products of engine combustion (Knothe, 2010).

In 2001, FAME was defined by the American Society for Testing and Materials (ASTM) as D6751, or biodiesel. As of March 2012, there are 148 biodiesel plants with annual production capacity of 1.4 billion gallons (NBB, 2012). FAME has a different chemical composition than petroleum-based diesel, known as ASTM D975, primarily in that 11% of its composition is oxygen. This has two main negative implications. The first is that FAME has a much higher cloud point than petroleum based fuel, and so cannot be used in high blend ratios in cold climates, and in aircraft, because it effectively freezes. The second is that FAME is hydrophilic, meaning that it mixes with water. This means that it cannot be transported by traditional infrastructure such as pipelines because FAME risks picking up water and the mixture contaminating jet fuel (Hileman et al. 2009). On the other hand, HEFA fuel is a synthetic fuel in that it has virtually the same chemical composition as petroleum based diesel and jet fuel. HEFA is defined as ASTM D975, and can be used in its pure form (in diesel engines). Part of the HEFA product slate is jet fuel. HEFA jet fuel has recently been approved by ASTM for use in jet engines up to a blend ratio of 50%.

In the literature, Knothe (2010) directly compares FAME and HEFA in terms of cost, environmental factors, energy content and fuel composition. Knothe concludes that both fuels have unique applications, namely, HEFA for jet fuel and compatibility with existing infrastructure and FAME in terms of its lubricity and environmental benefits. I add to this study by looking at an additional factor: a possible blend wall constraint for FAME due to infrastructure incompatibility. I also review literature estimates of the cost of FAME and HEFA to assess which fuel is likely to be produced in greater quantities.

3.3.2.1 FAME blend wall and Infrastructure Compatibility

As discussed above, FAME has different chemical properties than Diesel (D975) and so is not suitable for use in its pure form in diesel engines (Hileman, 2009, UOP, 2008). FAME (ASTM 6751) is usually blended with petroleum-based diesel (ASTM D975). There is therefore a limit to the maximum amount of FAME that can be consumed in the US, which is a function of total diesel consumption and the FAME blend ratio. The blend ratio can be calculated by finding the percentage of diesel engine manufactures that warranty FAME use, finding out what blend ratio they warrantee, and combining these numbers to find an aggregate blend ratio for the US. The National Biodiesel Board (NBB, 2012) reports that all major original equipment manufacturer (OEMs) in the U.S. market support B5 (5% blend of FAME and 95% conventional diesel) and lower blends, provided they are made with FAME meeting ASTM D6751. The NBB also reports that more than 60% of U.S. manufacturers support B20 (20% FAME, 80% petroleum diesel) or higher biodiesel blends in at least some of their equipment and that several more OEMs are completing testing and progressing toward support for B20 (Audi and Volkswagen) now that ASTM standards for B6-B20 blends have been published (ASTM D7467). The blend wall in year y can be calculated by solving equation 3.11

$$FBL(y) = B5_{\%} * 0.05 * dc(y) + B20_{\%} * 0.2 * dc(y) \tag{3.11}$$

where *FBL* is the FAME blend limit in year y, $B5_{\%}$ is the fraction of the US market that can use B5, $B2_{\%}$ is the fraction of the US market that can use B20 and dc is the projected US diesel consumption, y is the year. A blending constraint under RFS2 could arise if FBL(y) < Advanced biofuel mandate (y). Using diesel consumption data from EIA

(AEO, 2012) and plotting equation 3.11 over time, shown in figure 12, it can be seen that the RFS2 mandate is always lower than the B5 and B21 blend wall, or FBL(y) >> advanced biofuel mandate(y).

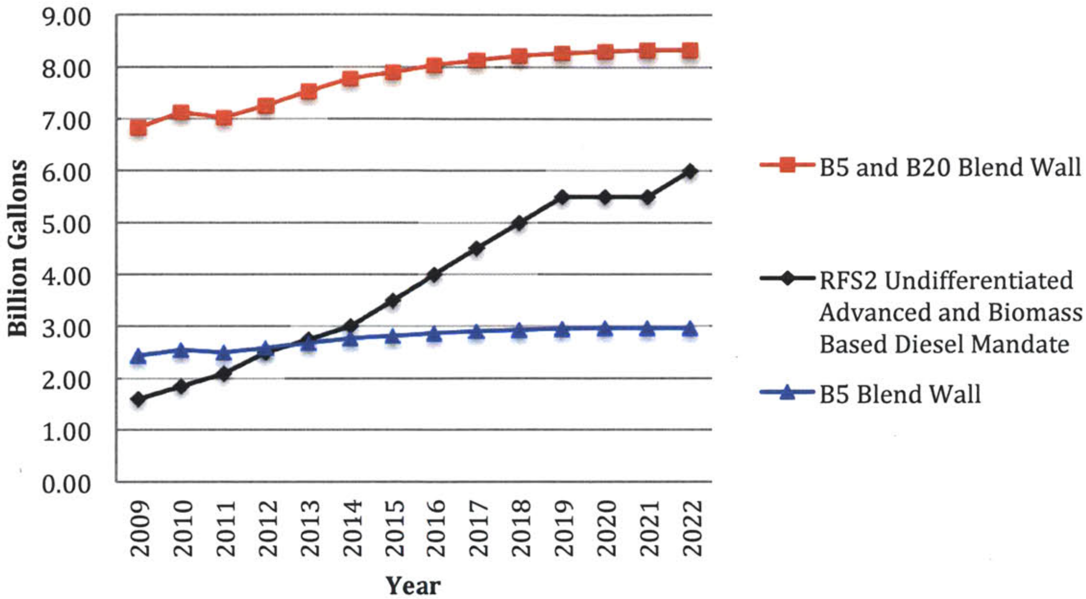

Figure 11. Biodiesel (FAME) Blend Wall Schematic.

Only in the case where only B5 is guaranteed by OEMs does a blending constraint arise. However, this is not the current situation (NBB, 2012). Therefore a blending constraint is unlikely to be a limitation to future FAME production. Note that while the theoretical FAME blend wall might not be a limitation to FAME in terms of the RFS2, FAME's incompatibility with existing infrastructure and feedstock supply constraints (discussed below) are likely to limit large-scale distribution.

3.3.2.2 Cost of FAME v. HEFA

If FAME or HEFA have a clear cost advantage, it would be likely that the lower cost fuel would be produced to meet the biomass based diesel and on into the undifferentiated advanced biofuel goal, taking into account feedstock and other limitations (see Appendix I). Several studies suggest that HEFA has lower capital and operating costs compared to FAME. Notably in 2005, UOP released a report for the US Department of Energy reporting HEFA as having lower capital and operating costs (UOP, 2005). Findings by Arena (2006) also suggest that HEFA is cheaper and in 2007 the US National Renewable Energy Lab (NREL, 2007) released a report citing Arena's findings. In an internal PARTNER paper, Pearlson (2011) found that HEFA from soy was 15% cheaper than FAME. However, these results are within a 30% margin of error, making exact comparison difficult. Theoretical work by Stumborg et al. (1996) also suggests that HEFA is cheaper, although no details on the nature of the process or the catalyst are offered. However, Knothe, (2010) concludes that there is not enough industry data for HEFA to accurately determine its cost. Further, the price of HEFA sold by the only US producer, Dynamic Fuels, cost \$5.70 in quarter 3 of 2011, compared to FAME's average cost at \$5.46 over the same period.

Based on these literature and industry estimates, it seems likely that the HEFA production process is cheaper than FAME. As Dynamic Fuels and other HEFA plants (in particular HEFA from soy oil and then algae) come online, the cost of production will likely decrease.

3.3.2.3 Other literature on the future of FAME and HEFA production

The US Energy Information Administration (EIA) forecasts (EIA, 2011) that FAME (biodiesel) production will hold constant at approximately 2 billion gallons per annum beyond 2022 (approximately the current FAME capacity in the US). The reason cited is supply constraints of soy oil and animal fat.[18] EIA project that by 2022, 1.69 billion gallons per year of biomass-derived liquid fuels will be produced, as seen in figure 12.

[18] Personal communication with Mac J. Statton (mac.statton@eia.gov, 202-586-7105)

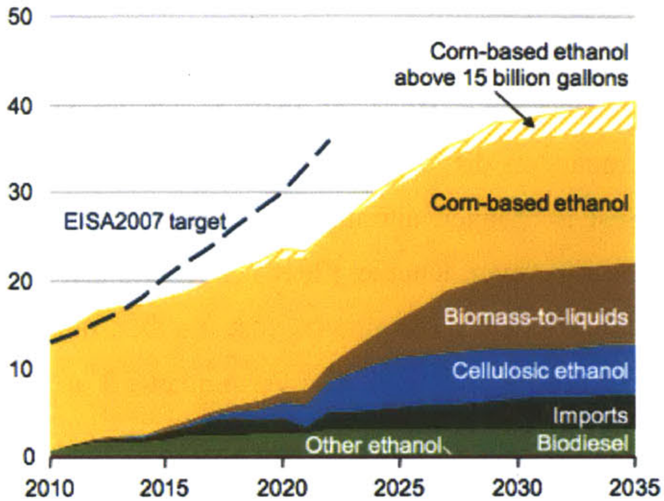

Figure 12. RFS2 2010-2035 and EIA forecasts. (EIA, 2012a).

EIA defines biomass-derived liquid fuels to include pyrolysis oils, biomass derived Fischer-Tropsch liquids, and renewable feedstocks used for the production of green diesel (HEFA). From the EIA estimate, it appears that animal fat and soy limitations will limit both the production of FAME and HEFA from these feedstocks. Alternative HEFA feedstocks such as algae, or pyrolysis oils, could therefore be used to meet the advanced biofuel goal.

3.3.2.4 Conclusion

Based on the above discussion three conclusions can be drawn. Firstly, a FAME blend wall is unlikely to be a direct limitation to FAME production. However, this does not mean that FAME's incompatibility with existing infrastructure will not limit its attractiveness and increase its cost. Secondly, literature estimates suggest that HEFA will be cheaper, although current industry estimates show HEFA as more expensive. Finally, literature estimates suggest that HEFA and FAME from animal fat and soy oil are likely to be limited by feedstock availability. Adding these findings to Knothe (2010), it seems likely that FAME will be used in small quantities as a lubricant and for its emissions reduction in diesel engines, and HEFA will be developed for unique high quality fuel purposes such as for military and commercial aviation. If new HEFA feedstocks such as algae become prevalent, increase in production could be expected.

3.3.3 Mandate Scenarios

In this section I define and apply a heuristic model of a renewable jet fuel mandate.

3.3.3.1 Methodology

A renewable jet fuel mandate would force blending of renewable jet fuel with conventional jet fuel. See section 3.1 for a brief discussion of how this could be implemented. Assuming that renewable jet fuel is more expensive than conventional jet fuel, a renewable jet fuel mandate would have the effect of increasing jet fuel prices. The effective increase in jet fuel prices can be calculated by multiplying the price premium of renewable jet fuel over conventional jet fuel, by the mandate divided by total US jet fuel consumption (blend ratio), as shown in equation 3.12

$$\Delta Jet_{mandate\ scenario,y} = (P_{RF} - P_{CF})_y * BR_y \tag{3.12}$$

where BR is the blend ratio, P_{RF} is the price of renewable jet fuel, P_{CF} is the price of conventional jet fuel, y is the year, and $\Delta Jet_{mandate\ scenario,y}$ is the net increase in jet fuel price in year y. The blend ratio in year y is found by dividing the *civil scenario* or the *civil less military scenario* by the jet fuel consumption forecasts from the EIA Annual Energy Outlook (2012b). Figure 14 shows the *civil scenario* and the *civil less military scenario,* as well as the EIA forecast of jet fuel consumption as a function of time.

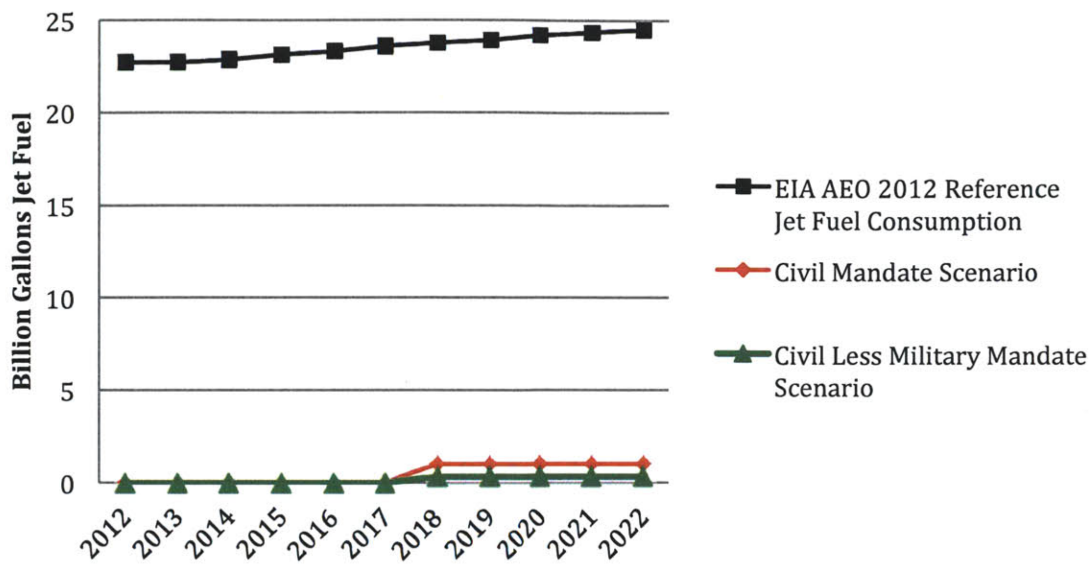

Figure 13. Gallons of jet fuel consumed in the US and scenarios.

GHG abatement induced by the mandate can be calculated by subtracting GHG emissions from the combustion of the mandated quantity of renewable jet fuel from the combustion of the mandated quantity of conventional jet fuel, as shown in equation 3.13

$$CO_2\,Abatement = Q_{mandate} * LCGHG_{PF} - Q_{mandate} * LCGHG_{RF} \tag{3.13}$$

where $LCGHG_{PF}$ is the life cycle greenhouse gas emissions of petroleum based jet fuel in metric tonnes/gallon and $LCGHG_{RF}$ is the life cycle greenhouse gas emissions of renewable jet fuel in metric tonnes/gallon and $Q_{mandate}$ and the mandate quantity in gallons.

3.3.3.2 Results

The effective increase in jet fuel price can be found by multiplying different renewable fuel cost premiums in year y, by the blend ratio, as shown in equation 3.12. There is much uncertainty around the production cost of renewable jet fuel. See section 3.2 for a discussion of industry and literature estimates of current and future renewable jet fuel production costs. I therefore use three different renewable fuel cost premiums ($0.2, $1.5 and $3) as an illustration of different impacts. This illustrative range captures the average 2011 biomass based diesel RIN prices at $1.44 (ERS, 2011), a high estimate of production cost which includes Dynamic Fuel's (2012) production cost, Bredehoeft et al.'s (2011) mid estimate for BTL and Carter's (forthcoming) estimate of algae, open pond wet. The lower cost estimate could include a scenario where a new technology is developed with lower costs, or current technology is improved.

The increases in jet fuel price for the *civil scenario* for the three different renewable fuel price premiums are plotted in figure 15, as calculated per equation 3.12. Jet fuel prices increase by between 3 and 12 cents per gallon.

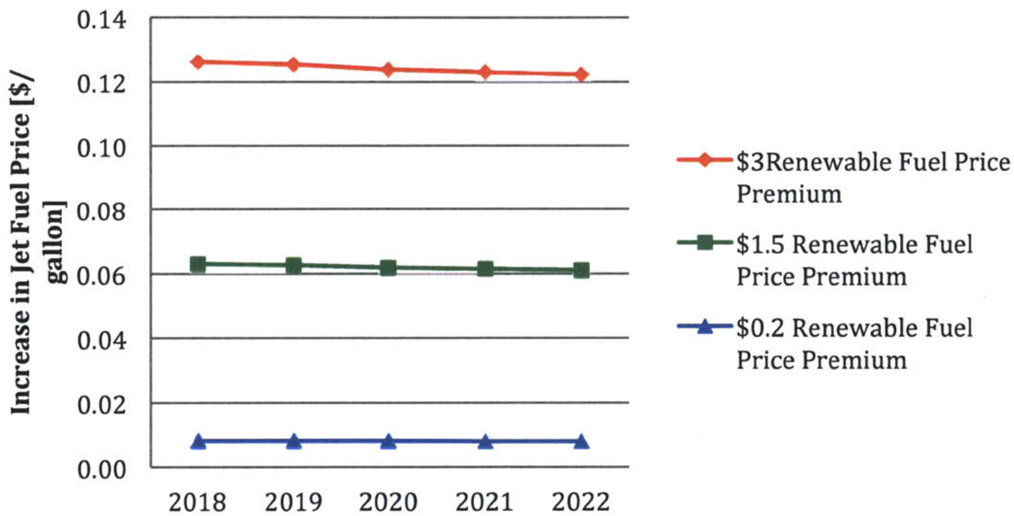

Figure 14. Increase in jet fuel price for different renewable fuel price premiums in the civil mandate scenario.

The increase in jet fuel prices relative to the reference scenario decreases over time as a result of forecast increases jet fuel consumption, as shown in figure 15, and the mandate remaining constant. The effective jet fuel price in year y can then be found by adding the delta increase in jet fuel price, $\Delta Jet_{mandate\ scenario,y}$, to the reference jet fuel price. I use the US EIA reference jet fuel price from the 2012 Annual Energy Outlook (EIA, 2012b). The resting jet fuel prices for the *civil scenario* are plotted in figure 16.

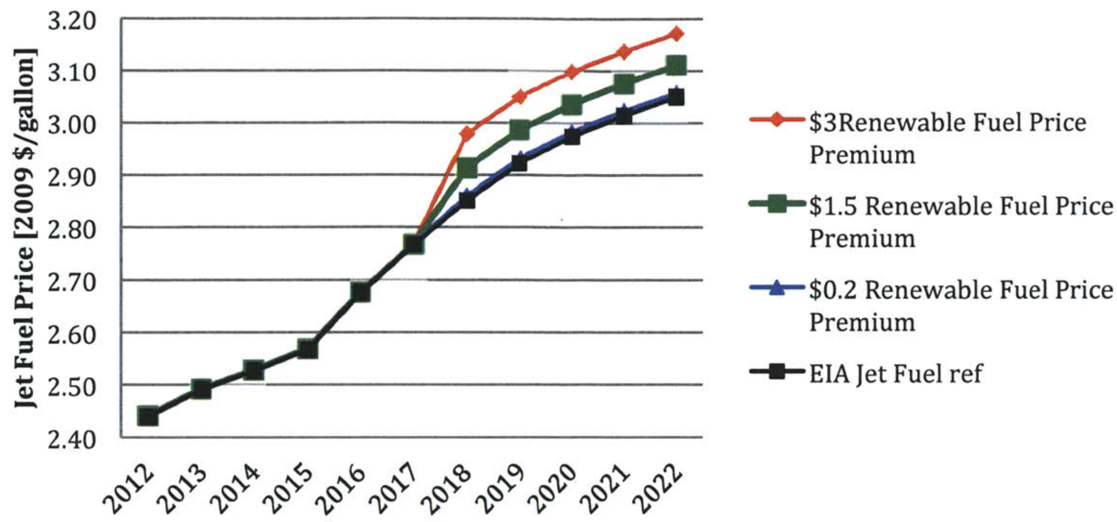

Figure 15. Civil scenario impacts on jet fuel prices.

Jet fuel prices rise by between 0.3-4.5% in 2018, as shown in figure 16, and table 7. In the scenario *civil less military* the impact is approximately three times less than the *civil scenario* as a result of the quantity of fuel mandated for civil aviation being three times smaller, as shown in table 6.

Table 10. Results.

Scenario	**Blend Ratio 2018 [%]**	**Blend Ratio 2022 [%]**	**Increase in Jet fuel Price, 2018, $1.5 Premium [%]**	**Increase in Jet fuel Price, 2022, $1.5 Premium [%]**
Civil Mandate Scenario	4.21	4.08	2.21	2.01
Civil less Military Mandate Scenario	1.40	1.36	0.74	0.67

The environmental benefits derived from the mandate stem primarily from reductions in GHG emissions[19]. Life cycle greenhouse gas emissions (LC-GHG) of petroleum based jet fuel and renewable jet fuel are used from Stratton et al (2010). The baseline value for conventional jet fuel is used (87.50 gCO_2e/MJ), which is equal to about 0.01

[19] There are also environmental benefits in terms of potential decreases in other emissions such as particulate matter and nitrous oxides as well as benefits from domestic fuel production. I do not quantify the benefits achieved in terms of these elements in this thesis.

tCO_2e/gallon of jet fuel. Stratton's estimates of LC-GHG emissions for renewable jet fuels vary widely depending on the production pathway, feedstock type, and land use change. There is also uncertainty around which renewable jet fuels will be produced between 2018 and 2022 (see section 3.2 for detailed discussion of this issue). I therefore select a representative range of renewable jet fuel LC-GHG emissions to take account of this uncertainty. At the high end, I use the EPA minimum percentage reduction on LC-GHG emissions for advanced biofuel and biomass-based diesel, at 50% (EPA, 2012c). This lies close to the range of soy to HEFA (60%), animal fat to HEFA (uncertain by ~50% as stated by EPA, 2012c), a medium algae estimate and a medium biomass to liquid estimate, from Stratton et al. (2010). On the low end I choose a 90% reduction in LC-GHG emissions, representing an optimistic estimate of biomass to liquid technology and algae technology coming online to meet the mandate between 2018 and 2022. The resulting *reference* and *civil scenario* GHG emissions are plotted in figure 17, with percentage change relative to the reference plotted in figure 18.

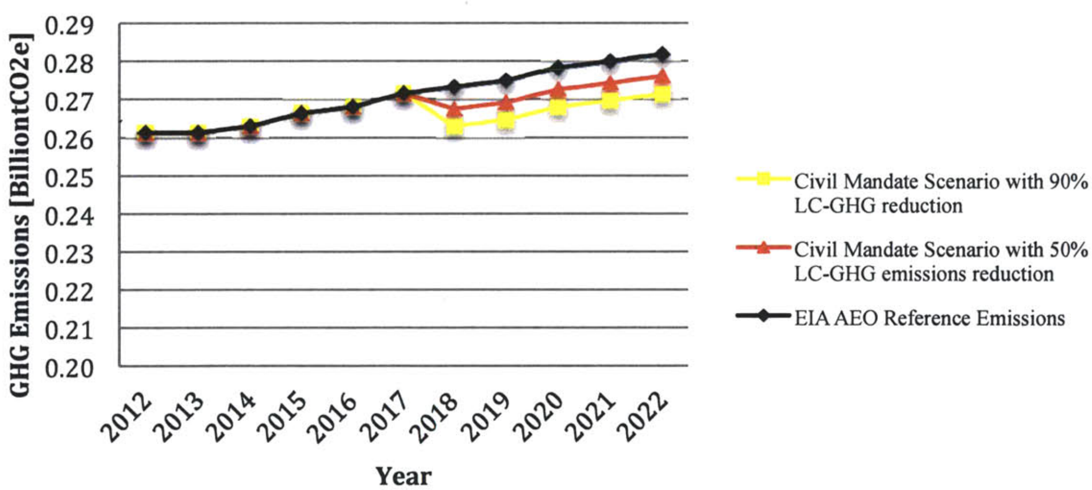

Figure 16. Reference and Civil Mandate Scenario GHG emissions for two estimates of LC-GHG.

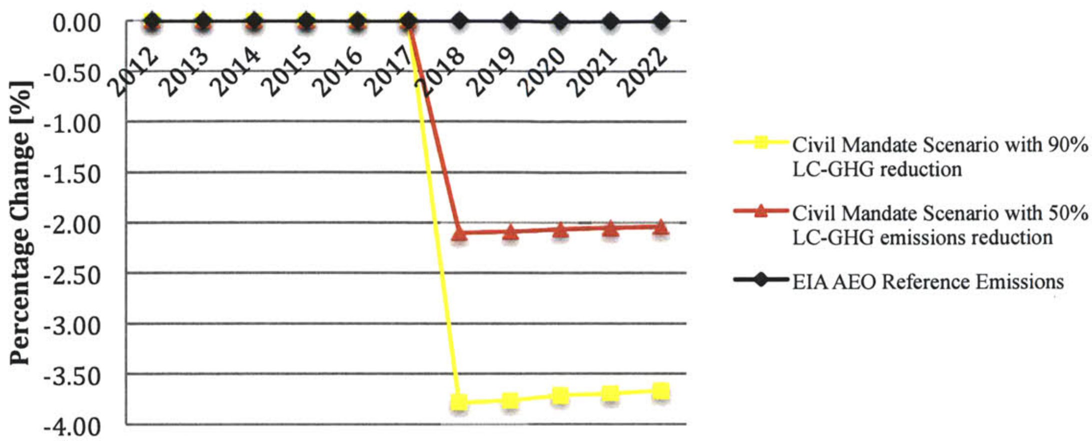

Figure 17. Percentage change between Reference and Civil Mandate Scenario GHG emissions for two estimates of LC-GHG.

Results are tabulated and shown in table 8, for both the *Civil Scenario* and the *Civil Less Military Scenario* and for both the 50% GHG emissions reduction scenario and the 90% emissions reduction scenario in 2018 and 2022.

Table 11. Scenario greenhouse gas emissions results.

Scenario	Reference GHG emissions [million tonnes]	Policy GHG emissions [million tonnes]	Policy GHG emissions reduction [million tonnes]	GHG Emissions Reduction rel. Reference [%]
Civil, 2018				
90% LC-GHG	273.24	262.9	10.34	3.78
50% LC-GHG	273.24	267.49	5.75	2.10
Civil less Military, 2018				
90% LC-GHG	273.24	269.79	3.45	1.26
50% LC-GHG	273.24	271.32	1.92	0.70
Civil, 2022				
90% LC-GHG	281.83	271.49	10.34	3.67
50% LC-GHG	281.83	276.08	5.75	2.04
Civil less Military, 2022				
90% LC-GHG	281.83	278.38	3.45	1.22
50% LC-GHG	281.83	279.91	1.92	0.68

As discussed above, the mandate remains constant, meaning that the emissions savings remains constant. However, there is projected growth in baseline civil aviation traffic (EIA, 2012b), which leads to a decrease in the GHG emissions reduction over time. The results in table 8 show that there would be between a 2 and 3.8% decrease in GHG emissions, for the *civil scenario* (1 billion gallons or renewable fuel per year) and between a 0.6 and 1.3% decrease in GHG emissions for the *civil less military scenario* (~333 million gallons of renewable fuel per year). This decrease in emissions would not offset continued growth in GHG emissions, and by 2022, policy GHG emissions would be larger than, or ~equal to, 2018 reference emissions, and continue growing at the same rate.

To offset the growth in emissions, the mandate would have to grow, as a percentage of jet fuel consumption over time, at the same rate as forecast growth in fuel consumption. However, the mandate achieves noticeable reductions in GHG emissions, with a relatively small impact on jet fuel prices (~4.5% with the high renewable fuel price premium of $3). Translating this increase in jet fuel price to a reduction in demand is possible using price elasticity of demand (PED) estimates. Using a conservative estimate of PED of -1 (Gillen et al., 2008) and assuming airline fuel costs at around 25% of total operating costs (ATA, 2008), the above increase in fuel price would results in a decrease in airline revenue tonne kilometers (RTK) of between about 1% and 0.1%

It is important to note that the above analysis does not say anything about how expensive this option of GHG mitigation is for airlines relative to other GHG mitigation options. In other words, the rational airline would presumably want to abate GHG at the lowest cost in a set of available options. Options may include paying for GHG emissions credits in an emissions trading scheme, such as the EU-ETS (Malina et al., 2012), or reducing cruise speed to optimal fuel consumption performance, at the cost of longer total flight times (Kar, 2010). Results from section 3.2 show where renewable jet fuels should be aiming in terms of cost and GHG emissions for cost-effective abatement. Results in section 3.3 show the impact of a mandate.

3.3.4 Conclusion

In this chapter I investigated the impact of two jet fuel mandate scenarios, modeled around the FAA renewable jet fuel goal of 1 billion gallons of renewable fuel per year by 2018 on US aviation. I identify an opportunity for the FAA goal to be implemented as part of the RFS2, with obligated parties having a renewable volume obligation of jet fuel each year. I find for a large range of renewable fuel price premiums (up to a $3/gallon premium) both mandate scenarios (1 billion and 333 million gallons of renewable jet fuel) would have a small impact on jet fuel prices (~4% increase per year in the worst case, 2% using current technology) with a small decrease in GHG emissions (~3% per year in the best case). GHG emissions would continue to grow, and pass 2018 emissions by 2022 in all but one scenario.

Chapter 4

4 Conclusion

In this thesis, I assessed the economic impact of the EU Emissions Trading Scheme on US aviation between 2012 and 2020, quantified greenhouse gas abatement cost goals of several renewable jet fuel production pathways, and estimated the impact of a hypothetical renewable jet fuel mandate on US aviation between 2018 and 2022.

I found that the EU Emissions Trading Scheme would only have a small impact on US airlines and emissions, and aviation operations would continue to grow by 3.11% p.a. compared to 3.35% p.a. in a business-as-usual scenario. If carriers pass on all additional costs to consumers, including the opportunity costs associated with free allowances, profits for US carriers will increase by as much as 56%. Windfall gains from free allowances may be substantial ($2.6 billion) under current allocation rules because airlines would only have to purchase about a third of the required allowances. However, an increase in the proportion of allowances auctioned would reduce windfall gains and profits for US airlines may decline. If airlines pass on allowance expenses only, no windfall gains are received, and aviation operations grow by 3.25% p.a.

For every emissions allowance that airlines purchase under the EU-ETS, a tonne of CO_2 will be abated out-of-sector in other industries or through the Clean Development Mechanism. In the FULL scenario, US airlines purchase approximately 71.13 million emissions allowances. This leads to out of sector abatement of 71.13 million tonnes CO_2 in the EU between 2012 and 2020 or about a third of US airlines GHG emissions on the North Atlantic. This can be compared to the approximately 1.6% in-sector CO2 emissions reduction due largely to reductions in aviation demand under the EU-ETS. All airlines purchase about 840 million emissions allowances which leads to the abatement of about 840 million tonnes CO_2 between 2012 and 2020, or approximately 2% of all EU emissions over the same period (UNFCC, 2008).

Under proposed EU legislation, airlines can use renewable jet fuel instead of purchasing emissions allowances. I find that the current allowance price would make it cheaper for airlines to purchase renewable jet fuel only if it has a price premium of 10 cents per gallon or less. It is important to note that this study cannot be used to evaluate the overall effectiveness of including aviation in the EU-ETS. In addition to considering benefits from avoided climate damages, evaluating overall effectiveness would require evaluating economic costs and benefits in all sectors in the economy.

In chapter 3 I found that a renewable jet fuel mandate of one billion gallons per year from 2018 to 2022 would have a small impact on fuel price, and consequently airline operations. This is primarily because only about 4% of fuel used by airlines would be renewable jet fuel. For a $1.50 renewable jet fuel premium, airline fuel costs increase by approximately 2% with abatement of between 2% and 4%. Emissions continue to grow and reach approximate 2018 levels by 2022. Such a mandate would force the production of renewable jet fuel and may have benefits in terms of hastening industry learning effects, as discussed by Stern (2007). This would ultimately drive down the abatement cost of renewable jet fuels, more rapidly than otherwise, to cost-effective levels.

I use the social cost of carbon, with a baseline value of $100/tCO_2e$, to calculate the societal cost-effective price premium of renewable jet fuel. I find that fuels can have a price premium of between 40c and $1.30, depending on life cycle greenhouse gas emissions reduction. However, the renewable jet fuels examined in this thesis, including the only commercially available fuel, have a currently estimated price premium of more than $2 per gallon and a calculated greenhouse gas abatement cost of more than $250/tCO_2e$. The only commercially available renewable jet fuel from hydroprocessed animal fat currently has a $2.70 premium over conventional jet fuel and consequently a high abatement cost at $400/tCO_2e$.

This thesis shows that the emerging renewable jet fuel industry still has some way to go to achieve greenhouse gas abatement costs, and therefore societal benefits, comparable to the social cost of carbon. It also shows that with the fuels examined, the EU emissions trading scheme, and the now defunct Waxman-Markey Bill, are currently lower cost options for airlines to abate greenhouse gas than renewable jet fuel, although they would not preclude the use of renewable fuels if they can be produced at lower cost.

Future research recommendations follow. Firstly, further research into renewable jet fuel production cost would be beneficial in terms of accurately estimating current and future renewable jet fuel greenhouse gas abatement cost and cost-effectiveness. Having additional cost data would also make estimating the impact of a renewable jet fuel mandate more accurate. However, the next step for estimating the impact of a renewable jet fuel mandate in the absence of more accurate cost data could be to use a probabilistic price and life-cycle greenhouse gas emissions distributions. This would give more informative results than the above scenario analysis.

Finally, to fully understand the cost of abatement of renewable jet fuel, the costs should ideally be compared to the greenhouse gas abatement costs of other aviation and economy-wide mechanisms, and ranked on a marginal abatement cost curve.

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6 Appendix

6.1 Appendix I: Overview of Renewable Fuel Legislation in the US

Renewable fuel policy in the US is motivated by three main concerns: high fuel prices, energy independence and security, and the environment. (Hileman, 2009, EIA, 2012 and EISA, 2007). Between July 2000 and July 2008, Western Texas Intermediate (WTI) crude oil prices increased by 244% (EIA, 2012), in 2010 the US imported more than two thirds of its domestic oil consumption[20], and concerns about climate change continue to grow.

In this appendix I explain the mechanics of the Renewable Fuels Standard II (RFS2), as specified in the Energy Independence and Security Act of 2007 (EISA, 2007). The RFS2 has its origins in the 2005 Energy Policy Act, which mandated the production of cornstarch-based ethanol (Energy Policy Act, 2005) through the Renewable Fuels Standard. In 2007, the Energy Independence and Security Act was passed. Title II of this act, *Energy Security through Increased Production of Biofuels*, updated the Renewable Fuels Standard into the renewable fuels standard II (RFS2). Under RFS2, total biofuel production was ramped up to 36 billion gallons of biofuel per year by 2022. Cornstarch based ethanol was capped at 15 billion gallons per year after 2015, with the majority of growth (21 billion of the 2022 total) coming from second-generation biofuels, or Advanced Biofuels, as shown in figure 19.

[20] Domestic oil production peaked in 1969 at close to 10,000 barrels per day. Since then there has been a steady decrease in domestic production and increase in imports. In 1994 imports of oil overtook domestic production, and in 2007 about two thirds (66.19 percent) of US oil consumed was imported.

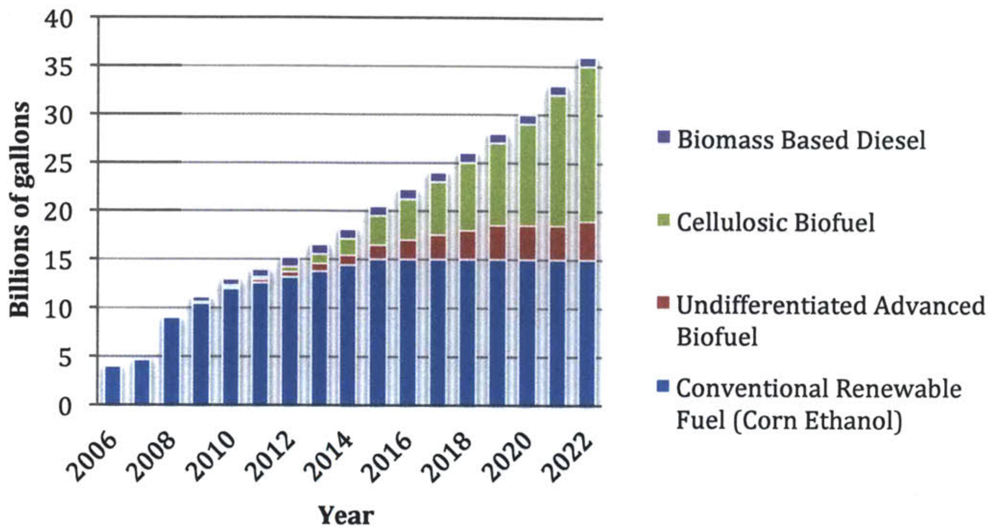
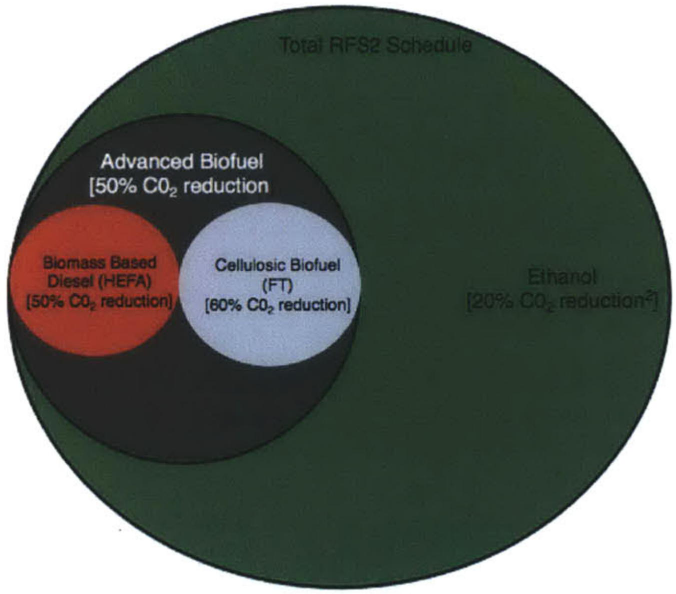


Figure 18. RFS2 Schedule under the Energy Independence and Security Act of 2007.

Advanced biofuel comprises cellulosic biofuel, biomass based diesel and undifferentiated advanced biofuel. Definitions under RFS2 are nested as shown in figure 20. This means that ethanol from cornstarch (conventional renewable fuel) meets only it's own and the total renewable fuel goal. Cellulosic biofuel meets its own, the advanced goal and the total goal, biomass based diesel meets its own and the undifferentiated advanced biofuel goals meets its own and the total goal.



[1] Diagram not to scale. RFS2 schedule changes on a yearly basis. Sets under *advanced biofuel* are relevant to aviation.
[2] For refineries built after 2007

Figure 19. Schematic of nested RFS2 fuel categories.

The EPA enforces RFS2 by mandating obligated parties to blend ethanol with gasoline and advanced biofuels with gasoline or diesel, depending on the distillation range of the renewable fuel. Obligated parties are importers or producers of petroleum products (refineries). Each obligated party is mandated a renewable volume obligation (RVO), calculated each year and shown in equation A.1

$$RVO_i = (RFStd_i \times GV_i) + D_{i-1} \qquad (A.1)$$

where $RFStd_i$ is the renewable fuel mandate in gallons for a given fuel category from figure 21, for calendar year i, GV_i is the nonrenewable gasoline and diesel volume, which is produced or imported by the obligated party in calendar year i in gallons and D_{i-1} is the renewable fuel deficit or carryover from the previous year in gallons.

Obligated parties are allowed to extend 20% of their RVO to the subsequent calendar year. The EPA fines obligated parties that fail to meet their RVO. To avoid the problem of refineries or importers not being able to procure renewable fuel for blending, the EPA devised a system of renewable fuel credit trading using the EPA Moderated Transaction System (EMTS), which was released for official use on July 1, 2010 (EPA, 2012b). EMTS facilitates the transactions and trading of renewable fuel credits, known as a Renewable Identification Numbers (RINs). A RIN is a 38-character numeric code that is generated by the producer or importer of renewable fuel. It represents a physical gallons of renewable fuel produced or imported in the US. The RIN code includes data including: whether or not a RIN is assigned to a batch of fuel (1=assigned/2=unassigned) (K), the year the batch is produced/imported (YYYY), the producing/importing company registration information (CCCC) the production facility registration information (FFFFF) , the producer assigned batch number (BBBBB), the equivalence value for the renewable fuel (biodiesel is 1.5 = "15") (RR), the renewable type code (1=cellulosic ethanol/2=non cellulosic ethanol fuel) (D), the RIN block starting number (SSSSSSSS) and the RIN block ending number (EEEEEEEE).

The RIN system works as follows (as shown in figure 21): when renewable fuel is produced at a plant such as Dynamic Fuels LCC in Geisther, Louisiana, a sample is sent to the EPA for screening. The EPA determines if the fuel meets life cycle greenhouse gas emissions targets and ASTM standards. If the fuel passes this test, each gallon is assigned a RIN, which is registered in the EMTS system. Different types of renewable fuel (FAME, HEFA, Ethanol etc.) are assigned different RINs, designated by the D code. Ethanol RINs have a value of one. Other renewable fuel RINs are assigned an equivalency value (EV) proportional to their energy content relative to ethanol, as shown in table 9.

Fuel Category (D Code)	EV
Ethanol:	1
Biodiesel (alkyl esters):	1.5
Renewable diesel:	1.7
Butanol:	1.3

Table 12. RIN equivalency values. Source (ERS, 2011).

RINs stay with the renewable fuel through the initial distribution system. When the fuel is blended into gasoline or diesel at a refinery or importer, the RIN is then separated from the renewable fuel. At year-end, each obligated party is required to meet its ROV by reporting RINs to the value of their ROV, for each fuel category (D code) (ERS, 2011).

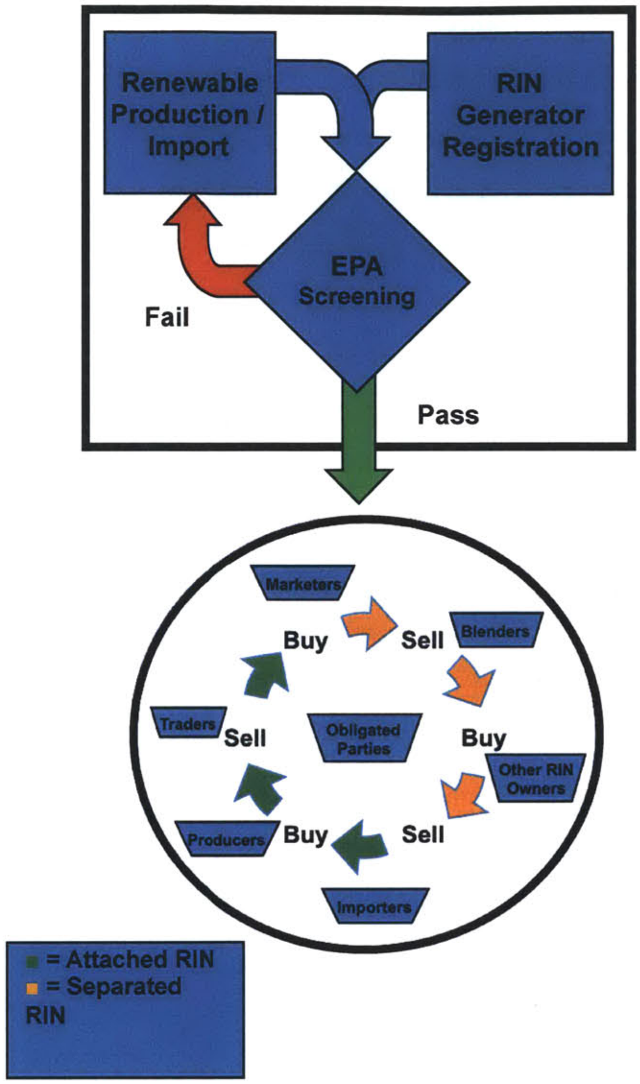


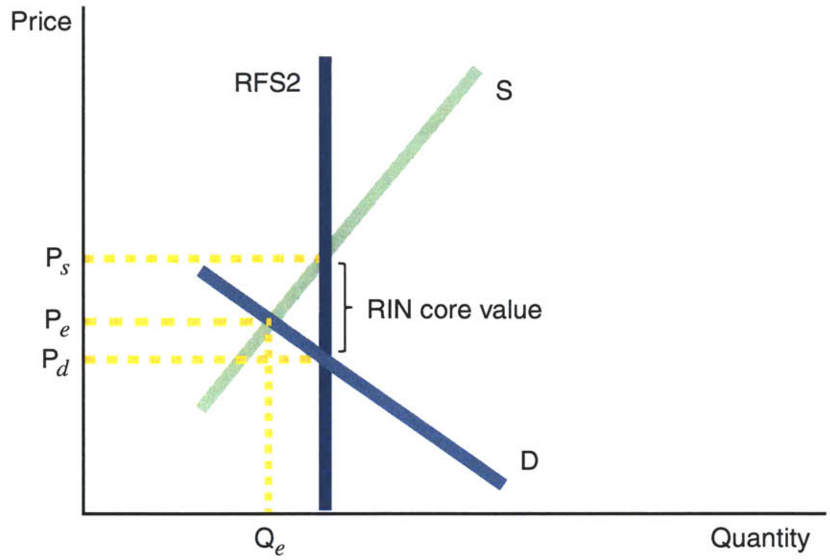
Figure 20. Mechanics of the RFS2. Source (EPA, 2008).

For example, a refinery that produces 1 billion gallons of gasoline and 50 million gallons of diesel in 2011, with a blend ratio of 10% for ethanol and 2% for biomass-based diesel, needs to purchase 100 million gallons of ethanol, and 1 million gallons of biomass based diesel in that year. The refinery would also need to meet the cellulosic biofuel goal the advanced biofuel goal and total biofuel goal.

If a refinery is able to exactly purchase its ROV in physical gallons of renewable fuel with attached RINs, it can report its RINs to the EPA at year-end. However, the EPA allows obligated parties to sell RINs that have been separated from renewable fuel to other refineries or registered parties, such as speculators. Therefore, if a refinery or importer is able to purchase more renewable fuel than it needs to meet its ROV, it can either keep the RINs for compliance for the next year (up to a maximum of 20% of its ROV), or it can sell the RINs to other refineries or speculators. This means that refineries or importers who are not able to procure renewable fuel can still meet their ROV by purchasing separated RINs on the EMTS. If an obligated party is unable to meet its ROV, it can appeal to the EPA for compliance the following year. The EPA fines noncompliant refineries (ERS, 2011).

In certain instances, the EPA can waive renewable fuel obligations. For example, in 2010 the EPA reduced the required volume of cellulosic biofuels from 100 million gallons, as specified by EISA, to 5 million gallons, due to the limited production of cellulosic biofuel. The EPA also made cellulosic biofuel waiver credits available to obligated parties for year-end compliance at $1.56 per gallon RIN (EPA, 2010a). In 2011 the EPA reduced the required volume of cellulosic biofuels from 250 million gallons, as specified by EISA, to 6.6 million gallons. The EPA also made cellulosic biofuel waiver credits available to obligated parties for end-of-year compliance at $1.13 per credit (EPA, 2012a). These waiver credits cannot be used in subsequent years, or to meet either the advanced or total renewable fuel goals.

RINs have a value, which is supposed to offset the higher production cost of renewable fuels compared to conventional fuels. For a given mandated biofuel quantity (for each fuel type, such as biomass based diesel) under RFS2, shown by the vertical line (RFS2) in figure 22, the core value of the RIN is equal to the difference between the marginal cost of production of biofuel (P_s) and the demand price (P_d).



S=Supply curve.
D=Demand curve.
RFS2=The mandated quantity.
Q_e=The equilibrium quantity without the mandate.
P_e=The equilibrium price without the mandate.
P_s=The supply price for biofuels at mandated quantity.
P_d=The demand price for biofuels at mandated quantity.
RIN=Renewable Identification Number.

Figure 21. Biofuel market with a binding mandate (ERS, 2011).

If the market equilibrium quantity exceeds the mandated quantity, then the RIN value will fall to zero. If the mandated quantity exceeds the market equilibrium quantity, then the core RIN value will be positive. The RIN value also includes transaction costs of meeting the RFS2, and can include a speculative component (ERC, 2011). Therefore even if a renewable fuel has an equivalent production cost relative to conventional fuel, the RIN price could still be slightly positive (3c/RIN in the case of corn ethanol), representing transaction costs through the EMTS and speculation (ERS, 2011). A high RIN price represents a high per unit cost of meeting the mandate, where the total cost of meeting a given mandate is equal to the RIN price multiplied by the mandated volume in gallons.

The RIN market, managed under the EMTS, ensures that the RFS2 mandate is met. Demand for RINs is generated by obligated parties who find it cheaper to purchase separated RINs than obtaining physical renewable fuel and blending. A supply of RINs comes from refineries and importers who blend more renewable fuel than their ROV, or from non-obligated parties such as small refineries.

The core value of RINs is driven by supply and demand. If there is a shortage of RINs to meet the total RFS2 mandated quantity, the price of RINs rise. If there is excess supply of RINs, the RIN price falls. In theory the RIN price should be high enough to allow biofuel producers to cover their production costs up to the RFS2 mandate. RIN prices are also affected by other factors such as tax credits, crude oil prices, feedstock prices and speculation.

A tax credit effectively reduces the production cost of renewable fuel, shifting the supply curve downward in figure 22 and reducing the RIN price. An increase in crude oil price increases the demand price, also reducing the RIN price. An increase in feedstock prices drives up renewable fuel production costs, and so shifts the supply curve upward, increasing the price of a RIN.

Speculation could change the quantity of RINs in the market in a given year, and therefore increase RIN prices. For example, if speculators predict that feedstock prices will increase in the following year, driving up the value of RINs the next year, they could buy RINs to sell the following year. This could potentially reduce the quantity of RINs in the market for that year, and so drive up the RIN price.

There is currently no renewable jet fuel RVO for obligated parties. Renewable jet fuel that is currently being produced or imported into the US is being used either by the military, or as diesel under the RFS2 (EPA, 2012c). Renewable jet fuel currently only falls under undifferentiated advanced biofuel category. However, in the future it may fall under cellulosic biofuel (biomass to liquid via Fischer-Tropsch fuels), or other pathways such as sugar to jet under undifferentiated advanced biofuel.

It is conceivable that in the future the EPA would include a jet fuel RVO for obligated parties, thereby mandating the production of renewable jet fuel. Such a possibility is explored in Chapter 3.

6.2 Appendix II: Cost Premium Goals

Table 13. LC-GHG emissions per Mega Joule.

	Low [gCO_2e/mj]	Baseline [gCO_2e/mj]	High [gCO_2e/mj]
Crude to conventional jet fuel	80.7	87.50	109.30
Crude to ULS jet fuel	84.6	89.10	111.20
Oil sands to jet fuel	97.9	103.40	139.00
Oil shale to jet fuel	84.1	121.50	141.00
Natural gas to F-T fuel	100.1	101.00	102.40
Coal to F-T fuel (no carbon capture)	174	194.80	208.00
Coal to F-T fuel (with carbon capture)	84.9	97.20	112.60
Switchgrass to F-T fuel (LUC-B0)	11.9	17.70	26.00
Switchgrass to F-T fuel (LUC-B1)	-4.4	-2.00	-1.70
Coal and Switchgrass to F-T fuel with CCS (LUC-B0)	12.4	56.90	99.80
Coal and Switchgrass to F-T fuel w/o CCS (LUC-B1)	6.9	53.00	97.80
Soy oil to HRJ (LUC-S0)	27.3	37.00	59.20
Soy oil to HRJ (LUC-S1)	81.7	97.80	141.70
Soy oil to HRJ (LUC-S2)	498.8	564.20	774.70
Palm oils to HRJ (LUC-P0)	22.5	30.10	38.10
Palm oils to HRJ (LUC-P1)	32.6	39.80	47.60
Palm oils to HRJ (LUC-P2)	153.2	166.00	193.30
Palm oils to HRJ (LUC-P3)	665.3	698.00	801.20
Rapeseed oil to HRJ (LUC-R0)	39.8	54.90	75.90
Rapeseed oil to HRJ (LUC-R1)	78.2	97.90	128.50
Jatropha oil to HRJ	31.8	39.40	45.10
Algae oil to HRJ	14.1	50.70	193.20
Salicornia to HRJ and F-T Fuel (LUC-H0)	30.5	47.70	66.10
Salicornia to HRJ and F-T Fuel (LUC-H1)	-19.2	5.80	32.20
Open Pond Wet (Carter)	48.6	56.57	234.68
Flat Panel Wet (Carter)	28.46	28.88	234.34

Table 14. LC-GHG emissions per gallon.

	Low [tCO_2/gallon]	Baseline [tCO_2/gallon]	High [tCO_2/gallon]
Crude to conventional jet fuel	0.01	0.01	0.01
Crude to ULS jet fuel	0.01	0.01	0.01
Oil sands to jet fuel	0.01	0.01	0.02
Oil shale to jet fuel	0.01	0.02	0.02
Natural gas to F-T fuel	0.01	0.01	0.01
Coal to F-T fuel (no carbon capture)	0.02	0.02	0.03
Coal to F-T fuel (with carbon capture)	0.01	0.01	0.01

Switchgrass to F-T fuel (LUC-B0)	0.00	0.00	0.00
Switchgrass to F-T fuel (LUC-B1)	0.00	0.00	0.00
Coal and Switchgrass to F-T fuel with CCS (LUC-B0)	0.00	0.01	0.01
Coal and Switchgrass to F-T fuel w/o CCS (LUC-B1)	0.00	0.01	0.01
Soy oil to HRJ (LUC-S0)	0.00	0.00	0.01
Soy oil to HRJ (LUC-S1)	0.01	0.01	0.02
Soy oil to HRJ (LUC-S2)	0.06	0.07	0.10
Palm oils to HRJ (LUC-P0)	0.00	0.00	0.00
Palm oils to HRJ (LUC-P1)	0.00	0.01	0.01
Palm oils to HRJ (LUC-P2)	0.02	0.02	0.02
Palm oils to HRJ (LUC-P3)	0.08	0.09	0.10
Rapeseed oil to HRJ (LUC-R0)	0.01	0.01	0.01
Rapeseed oil to HRJ (LUC-R1)	0.01	0.01	0.02
Jatropha oil to HRJ	0.00	0.00	0.01
Algae oil to HRJ	0.00	0.01	0.02
Salicornia to HRJ and F-T Fuel (LUC-H0)	0.00	0.01	0.01
Salicornia to HRJ and F-T Fuel (LUC-H1)	0.00	0.00	0.00
Open Pond Wet (Carter)	0.01	0.01	0.03
Flat Panel Wet (Carter)	0.00	0.00	0.03

Table 15. LC-GHG normalized to baseline conventional jet fuel.

	Low LC-GHG emissions normalized to conventional jet fuel	Baseline LC-GHG emissions normalized to conventional jet fuel	High LC-GHG emissions normalized to conventional jet fuel
Crude to conventional jet fuel	0.89	1.00	1.25
Crude to ULS jet fuel	0.93	1.02	1.27
Oil sands to jet fuel	1.08	1.14	1.53
Oil shale to jet fuel	0.93	1.34	1.55
Natural gas to F-T fuel	1.10	1.11	1.13
Coal to F-T fuel (no carbon capture)	1.91	2.14	2.29
Coal to F-T fuel (with carbon capture)	0.93	1.07	1.24
Switchgrass to F-T fuel (LUC-B0)	0.13	0.19	0.29
Switchgrass to F-T fuel (LUC-B1)	-0.05	-0.02	-0.02
Coal and Switchgrass to F-T fuel with CCS (LUC-B0)	0.14	0.63	1.10
Coal and Switchgrass to F-T fuel w/o CCS (LUC-B1)	0.08	0.58	1.08
Soy oil to HRJ (LUC-S0)	0.30	0.41	0.65
Soy oil to HRJ (LUC-S1)	0.90	1.08	1.56
Soy oil to HRJ (LUC-S2)	5.49	6.21	8.52
Palm oils to HRJ (LUC-P0)	0.25	0.33	0.42
Palm oils to HRJ (LUC-P1)	0.36	0.44	0.52
Palm oils to HRJ (LUC-P2)	1.69	1.83	2.13

Palm oils to HRJ (LUC-P3)	7.32	7.68	8.81
Rapeseed oil to HRJ (LUC-R0)	0.44	0.60	0.83
Rapeseed oil to HRJ (LUC-R1)	0.86	1.08	1.41
Jatropha oil to HRJ	0.35	0.43	0.50
Algae oil to HRJ	0.16	0.56	2.13
Salicornia to HRJ and F-T Fuel (LUC-H0)	0.34	0.52	0.73
Salicornia to HRJ and F-T Fuel (LUC-H1)	-0.21	0.06	0.35
Open Pond Wet (Carter)	0.53	0.62	2.58
Flat Panel Wet (Carter)	0.31	0.32	2.58

Table 16. Cost premium goals of low (\$25/tCO_2e), medium (\$100/tCO_2e) and high (\$175/tCO_2e) SCC.

	SCC Low, LC-GHG High	Price Premium SCC Med	SCC High, LC-GHG Low
Crude to conventional jet fuel	-0.07	0.00	0.23
Crude to ULS jet fuel	-0.08	-0.02	0.14
Oil sands to jet fuel	-0.15	-0.16	-0.15
Oil shale to jet fuel	-0.16	-0.39	0.15
Natural gas to F-T fuel	-0.04	-0.13	-0.20
Coal to F-T fuel (no carbon capture)	-0.37	-1.31	-1.84
Coal to F-T fuel (with carbon capture)	-0.07	-0.08	0.13
Switchgrass to F-T fuel (LUC-B0)	0.21	0.93	1.75
Switchgrass to F-T fuel (LUC-B1)	0.29	1.17	2.11
Coal and Switchgrass to F-T fuel with CCS (LUC-B0)	-0.03	0.43	1.74
Coal and Switchgrass to F-T fuel w/o CCS (LUC-B1)	-0.02	0.48	1.86
Soy oil to HRJ (LUC-S0)	0.10	0.68	1.41
Soy oil to HRJ (LUC-S1)	-0.16	-0.09	0.20
Soy oil to HRJ (LUC-S2)	-2.16	-5.98	-9.02
Palm oils to HRJ (LUC-P0)	0.17	0.77	1.51
Palm oils to HRJ (LUC-P1)	0.14	0.65	1.29
Palm oils to HRJ (LUC-P2)	-0.32	-0.95	-1.38
Palm oils to HRJ (LUC-P3)	-2.25	-7.68	-12.71
Rapeseed oil to HRJ (LUC-R0)	0.05	0.46	1.13
Rapeseed oil to HRJ (LUC-R1)	-0.12	-0.09	0.28
Jatropha oil to HRJ	0.14	0.65	1.31
Algae oil to HRJ	-0.32	0.51	1.70
Salicornia to HRJ and F-T Fuel (LUC-H0)	0.08	0.55	1.34
Salicornia to HRJ and F-T Fuel (LUC-H1)	0.19	1.08	2.44
Open Pond Wet (Carter)	-0.45	0.43	0.94
Flat Panel Wet (Carter)	-0.45	0.78	1.38

6.3 Appendix II: Sensitivity of GHG abatement Cost Results

Table 17. Literature Estimates Assumptions.

Pathway	Economic Source	Price Assumption	Low	Med	High	Delta LC-GHG Source
Soy to HEFA (feedstock 5 year average)	Pearlson, 2011	5 year average: soybean oil price ($2.62), jet fuel price ($2.25)	6500 bpd	4000 bpd	2000 bpd	Stratton (2010), LUC S0
Soy to HEFA (feedstock current)	Pearlson, 2011, Worldbank,	2012 for soybean oil price 4/2012 of $4.29/gallon	6500 bpd	4000 bpd	2000 bpd	Stratton (2010), LUC S0
Biomass-to-liquid via F-T	Bredehoeft, 2011		No Feedstock Cost	Average estimate	High Estimate	Stratton (2010),
Algae Open Pond Wet	Carter, Forthcoming					Carter, Forthcoming
Algae Flat Panel Wet	Carter, Forthcoming					Carter, Forthcoming

Table 18. LC-GHG Sensitivity Results.

Literature Estimates	Low Price	Average Price	High Price	Price Premium Low	Price Premium Med	Price Premium High	Life cycle GHG emissions normalized to conventional jet fuel	MAC Low -	MAC Med	MAC High +
Soy to HEFA (feedstock 5 year average)	3.80	3.98	4.38	1.55	1.73	2.13	0.41	26.41	253.83	58.69
Soy to HEFA (feedstock current)	5.52	5.78	6.36	2.44	2.70	3.28	0.41	38.55	398.16	85.66
Biomass-to-liquid via F-T	2.38	8.93	16.07	-0.70	5.85	12.99	0.19	707.68	632.05	771.43
Algae Open Pond Wet	5.81	7.71	18.54	2.73	4.63	15.46	0.62	437.67	1066.54	2494.73
Algae Flat Panel Wet	19.56	30.66	47.42	16.48	27.58	44.34	0.32	1415.44	3516.92	2137.19